A MATHEMATICAL MODEL
OF THE
HUMAN THERMAL SYSTEM

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FINAL REPORT

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1. Introduction

The objective of this contract is to produce for NASA a program which provides a more detailed model of the human thermal system than the twelve-node model being used at the present time. Calculations are based on the transient state heat conduction equation expressed in cylindrical coordinates. Subject to the restriction that the human body can be subdivided into a number of cylindrical elements in each of which axial symmetry prevails, the program permits one to calculate the thermal history at any location in the body.

Since as many as twenty radial points are used in a given element, accounting for variations in such physical properties as specific heat, thermal conductivity, blood perfusion rate, and heat generation rate, is possible in this program. Hence, large masses of tissue such as the lungs, bone, muscle, fat, and skin are readily discernible in this program.

The principal mechanisms for thermal regulation in the human are vasodilation and sweating in a warm environment, or vasoconstriction and shivering in a cold environment. One requirement of this contract is that the basic control equations used in the current twelve-node MSC model be incorporated into this program.

This report describes the program that was written to fulfill the requirements of this contract.

2. The Mathematical Model

A description of the basic mathematical model is given in a paper (1) published previously by the author of this report. For the convenience of readers, this paper is reproduced in Appendix A.

The program which was available at the beginning of this contract provided a description of the passive human thermal system. It made no provision for changes in such physiological variables as capillary perfusion rates and local sweat rates. On the other hand, the model in use at the Manned Spacecraft Center did contain control equations which were to be incorporated into our model. These equations are presented below. In referring to the MSC equations, which will be numbered with the prefix M in this report, the subscripts are to be identified with the following physical elements:

Table I. Identification of the MSC Elements

Subscript	MSC Identification
1	Head core
2	Head skin
3	Trunk core
4	Trunk muscle
5	Trunk skin
6	Arm muscle
7	Arm skin
8	Hand muscle
9	Hand skin
10	Leg muscle
11	Leg skin
12	Foot muscle
13	Foot skin
14	Central blood

The basic hypothesis on which the MSC control equations are based is that there exists a "set-point" temperature for each of the elements identified above. Whenever the tissue temperature exceeds the set-point, there is a tendency for vasodilatation and sweating to occur. However, the head core temperature must exceed its set-point before the responses can actually occur. Similarly, when the tissue temperatures fall below their set-points, there is a tendency for vasoconstriction and shivering to occur. The shivering response will not be elicited until the head core temperature falls below its set-point. However, vasoconstriction does not depend on the head core temperature.

Table II. Set-point Temperatures for the MSC Control Equations

Element, I	Set-point, TS(I)
1	98.46
2	96.12
3	98.64
4	97.74
5	94.68
6	96.84
7	93.24
8	97.56
9	96.84
10	97.20
11	91.44
12	97.56
13	96.30
14	98.10

Deviations from the set-points are evaluated as follows:

```
      DO  52  I = 1, 14
      TEST(I) = T(I) - TS(I)
      WARM(I) = 0.0
      COLD(I) = 0.0
      IF (TEST(I)) 53, 54, 55....                    (M-1)
53    COLD(I) = - TEST(I)
54    GO TO 52
55    WARM(I) = TEST(I)
52    CONTINUE
```

Weighted sums of the warm and cold stimuli for the skin and muscle elements are then formed as follows:

$$\begin{aligned}\mathrm{WARMS} = {} & 0.056 * \mathrm{WARM}(2) \\ & + 0.276 * \mathrm{WARM}(5) \\ & + 0.173 * \mathrm{WARM}(7) \\ & + 0.043 * \mathrm{WARM}(9) \\ & + 0.383 * \mathrm{WARM}(11) \\ & + 0.069 * \mathrm{WARM}(13)\end{aligned} \qquad \text{(M-2)}$$

$$\begin{aligned}\mathrm{WARMM} = {} & 0.417 * \mathrm{WARM}(4) \\ & + 0.190 * \mathrm{WARM}(6) \\ & + 0.393 * \mathrm{WARM}(10)\end{aligned} \qquad \text{(M-3)}$$

$$\begin{aligned}\mathrm{COLDS} = {} & 0.056 * \mathrm{COLD}(2) \\ & + 0.276 * \mathrm{COLD}(5) \\ & + 0.173 * \mathrm{COLD}(7) \\ & + 0.043 * \mathrm{COLD}(9) \\ & + 0.383 * \mathrm{COLD}(11) \\ & + 0.069 * \mathrm{COLD}(13)\end{aligned} \qquad \text{(M-4)}$$

$$\begin{aligned}\mathrm{COLDM} = {} & 0.417 * \mathrm{COLD}(4) \\ & + 0.190 * \mathrm{COLD}(6) \\ & + 0.393 * \mathrm{COLD}(10)\end{aligned} \qquad \text{(M-5)}$$

These quantities are used to calculate the sweat rate, SWEAT; increase in capillary perfusion rate, DILAT; increase in metabolic rate due to shivering, QSHIV; and decrease in capillary perfusion rate, STRIC.

$$\mathrm{SWEAT} = \mathrm{WARM}(1) * (\mathrm{WARMA} + \mathrm{WARMM}) * 73.4814 \qquad \text{(M-6)}$$

$$\mathrm{DILAT} = 0.25 * \mathrm{SWEAT} \qquad \text{(M-7)}$$

$$\mathrm{QSHIV} = \mathrm{COLD}(1) * (\mathrm{COLDS} + \mathrm{COLDM}) * 73.4814 \qquad \text{(M-8)}$$

STRIC = (COLDS + COLDM) * 0.01961 (M-9)

Since either WARM(1) or COLD(1) must be zero, it is apparent that this model precludes simulaneous sweating and shivering. However, it is possible to generate simultaneous inputs from STRIC and SWEAT.

The responses defined above are then distributed among the various elements. When the subject is sweating, latent heat removal is assigned to the skin nodes according to the following equations.

QLAT(2) = 0.10 * SWEAT

QLAT(5) = 0.60 * SWEAT

QLAT(7) = 0.10 * SWEAT (M-10)

QLAT(9) = 0.02 * SWEAT

QLAT(11) = 0.16 * SWEAT

QLAT(13) = 0.02 * SWEAT

Even when the subject is not sweating, there is latent heat removal from the skin owing to insensible perspiration. The magnitude of this loss is assumed to be

6.66 * A(I) * (VPP(T(I) - VPP(TDEW))

in which A(I) = surface area of the I^{th} element of skin

VPP = vapor pressure function routine, and

TDEW = dew point of the environment.

The insensible loss is added to the sweat loss to obtain the total latent component. A final check has to be made to establish that the maximum rate of evaporation, which is established by mass transfer considerations, is not exceeded. The maximum rate of latent heat removal is given by

EMX(I) = 0.126 * SQRT(VCAB/PCAB) * (TCAB + 460.0 **
1.04 * A(I) * VPP(T(I)) - VPP(TDEW)) (M-11)

In defining heat generation rates for the various elements, it is assumed that the rate remains at the basal level in the core and skin elements. The rates in the muscle elements become greater than the basal rate when the subject is shivering or doing work. Hence, we have used:

QMET IS BASAL METABOLIC FOR ALL NODES EXCEPT NODES WHICH ARE AFFECTED BY WORK

QMET(1) = 49.2825

QMET(2) = 0.3968

QMET(3) = 179.3536

QMET(4) = 17.0624 + .417 * (WORK + QSHIV)

QMET(5) = 2.0236

QMET(6) = 6.19 + .190 * (WORK + QSHIV) (M-12)

QMET(7) = 1.23

QMET(8) = 2.3014

QMET(9) = .3174

QMET(10) = 18.5702 + .393 * (WORK + QSHIV)

QMET(11) = 2.8172

QMET(12) = 4.5235

QMET(13) = .4761

Similarly, the equations defining blood flow rates for the various elements contain the assumption that there is no change in the two core elements. Flow rates to the muscle and skin elements increase or decrease depending on the relative values of DILAT and STRIC.

BLOODFLOW (IN POUNDS/HR)

BF(1) = 105.897

BF(2) = 2.647 + .056 * DILAT

```
BF(3) = 503.013
BF(4) = 22.062 + QMET(4) - STRIC
BF(5) = 2.2062 + .3 * DILAT - STRIC                    (M-13)
BF(7) = 1.103 + .2 * DILAT - STRIC
BF(8) = 1.103 - STRIC
BF(9) = 8.824 + .1 * DILAT - STRIC
BF(6) = 6.618 + QMET(6) + BF(9) - STRIC
BF(11) = 2.206 + .294 * DILAT - STRIC
BF(12) = 2.206 - STRIC
BF(13) = 6.618 + .05 * DILAT - STRIC
BF(10) = 17.649 + QMET(10) + BF(13) - STRIC
```

Negative values of BF are not permitted.

Since our program is considerably more detailed than the MSC program, a different numbering system is required for identifying the elements. We have subdivided the body into fifteen major cylindrical elements which are designated according to the following table.

Table III. Identification of the Major MAPS Elements

First Subscript	MAPS Identification
1	Chest
2	Abdomen
3	Head
4	Proximal segment of right leg
5	Medial segment of right leg
6	Distal segment of right leg

Table III. (Continued)

First Subscript	MAPS Identification
7	Proximal segment of left leg
8	Medial segment of left leg
9	Distal segment of left leg
10	Proximal segment of right arm
11	Medial segment of right arm
12	Distal segment of right arm
13	Proximal segment of left arm
14	Medial segment of left arm
15	Distal segment of left arm

Each major element is divided radially into annular shells. These are numbered starting with 1 on the axis of the cylinder and progressing to JB(I) at the outer surface. Hence, T(4,1) denotes the centerline temperature in the right thigh and T(4,15) denotes the corresponding skin temperature when fifteen radial points are used in the thigh.

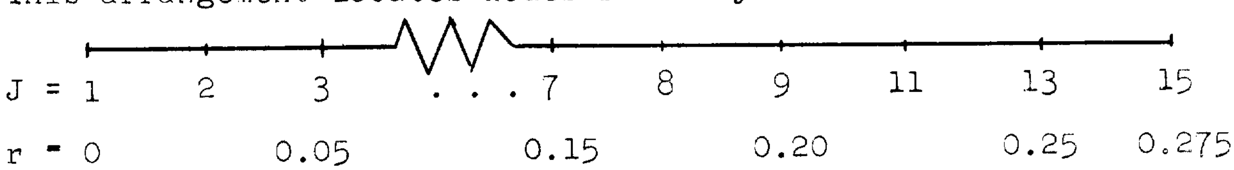
It is generally desirable to use coarse radial subdivision in regions where temperature gradients are small and finer subdivisions in regions where large temperature gradients exist. Therefore, we have included in our program the option for assigning as many as five radial step sizes in any given element. H(I,K) denotes the K-th radial step size used in the I-th element, and JH(I,K) denotes the radial node at which the use of H(I,K) begins. Hence, if fifteen radial nodes are used in the fourth element for a

total of fourteen shells, and the radial step size is 0.025 for the first eight subdivisions and 0.0125 for the remaining six, we would make the following assignment for JH(4,K) and H(4,K)

$$\begin{aligned} JH(4,1) &= 1 \\ JH(4,2) &= 9 \\ JH(4,3) &= JH(4,4) = JH(4,5) = 20 \end{aligned} \tag{1}$$

$$\begin{aligned} H(4,1) &= 0.025 \\ H(4,2) &= 0.0125 \\ H(4,3) &= H(4,4) = H(4,5) = 0.0 \end{aligned} \tag{2}$$

This arrangement locates nodes radially as shown below.



It should be noted that five is the maximum number of step sizes that can be used. Fewer than five can be used by simply assigning values greater than JB(I) to the unused JH's.

Physical properties are assigned in much the same way. The annular shells in a given element can be grouped together into as many as give regions, in each of which the physical properties are uniform. JP(I,K) denotes the radial node at which the K-th region begins. If, in the preceding example, we set

$$\begin{aligned} JP(4,1) &= 1 \\ JP(4,2) &= 2 \\ JP(4,3) &= 11 \\ JP(4,4) &= 13 \\ JP(4,5) &= 20, \end{aligned} \tag{3}$$

we have a cylindrical core of radius 0.025 along the axis, a thick annular region extending to r = 0.225, and two outer shells each having a thickness of 0.025. Hence, the large arteries and veins could be assigned to the inner cylinder, the thick shell could be considered to be muscle, and the outer shells could represent subcutaneous fat and skin. In each of these regions, one must assign values for the density, specific heat, and thermal conductivity of tissue; density and specific heat of blood in the arterial and venous pools; metabolic heat generation rate; capillary perfusion rate; and heat transfer coefficients for transfer of heat from blood in the arterial and venous pools to adjacent tissue.

Some of these quantities, such as density, specific heat, and thermal conductivity, define the passive physical structure of the subject. These quantities are important in determining the thermal response of the subject, but they do not change under the stimulus of thermal stress. Hence, they are read in as data and remain constant during the computation.

Other quantities, notably the capillary perfusion and heat generation rates, do participate actively in the thermal regulatory process and must be evaluated continuously during the computation. One of the objectives of this project is to incorporate the MSC control equations into our model. Since these equations define blood flow rates and heat generation rates in large segments, such as the trunk core, muscle, and skin, it is necessary to define an algorithm for distributing these quantities throughout the various segments of our model. We have chosen to do this by defining two pairs of numbers for each of our property regions. Each pair defines an index identifying one of the MSC control equations and the fraction of that quantity which is to be assigned to the region in question. For example, in the skin region of the distal segment of the left arm, which is property region (15,3) in our program, we have used

LV1(15,3) = 7, F1 = 0.11169

LV2(15,3) = 9, F2 = 0.5

Hence, 11.169 percent of the blood flow assigned to the skin of both arms (element 7) and 50.0 percent of the flow

to the hand skin (element 9) in the MSC program is assigned to the skin of the distal arm segment in our program. This blood flow is then uniformly distributed throughout that region as follows. Two weight factors are defined

$$CV1(I,K) = F1/VOL(I,K) \tag{4}$$

and

$$CV2(I,K) = F2/VOL(I,K) \tag{5}$$

in which VOL(I,K) = volume of the K-th property region in the I-th element. These factors define the relationship between capillary perfusion rates in our model and blood flow rates in the NASA as follows

$$L1 = LV1(I,K) \tag{6}$$

$$L2 = LV2(I,K) \tag{7}$$

$$QC(I,K) = CV1(I,K) * BF(L1) + CV2(I,K) * BF(L2) \tag{8}$$

In the current version of our program the same weight factors are used to define the metabolic heat generation densities.

$$HMET(I,K) = CV1(I,K) * QMET(L1) + CV2(I,K) * QMET(L2) \tag{9}$$

This scheme has several features to recommend it. One is that the cardiac output and gross metabolic rates are identical in the two programs. Another is that there is close correspondence between rates assigned to such elements as the head, trunk, and extremities in the two programs. The third is that it is relatively easy to change the blood flow pattern between segments, or within a given segment, while holding the cardiac output constant.

It should also be noted that an allowance for clothing can be accomplished easily with our program. Given an appropriately defined set of parameters for a nude subject, one merely assigns additional radial nodes in the region occupied by clothing. Loosely fitting garments can be separated from the skin of the subject by a region having the physical characteristics of air. The high thermal resistance of even a thin layer of air and cloth causes appreciable temperature differences between clothed and unclothed areas of skin.

Heat transfer from an exposed surface to the environment occurs by convection, radiation, and evaporation. For each element the convective component is defined in terms of a heat transfer coefficient HTC(I). The thermal flux at the surface of the I-th element is given by

$$\mathrm{HTC(I)} * (\mathrm{TSUR} - \mathrm{TE(I)})$$

in which the surface temperature TSUR = T(I,JB(I)). TE(I) is the ambient air temperature for element I.

Precise evaluation of the radiant component for a given element is a difficult task. We have avoided this problem by assuming that the use of a radiant heat transfer coefficient provides sufficient accuracy. Define

$$\begin{aligned} \mathrm{HRAD(I)} = 0.1719 \times 10^{-8} * \mathrm{EMIS(I)} * (&\mathrm{TSUR}^3 \\ &+ \mathrm{TSUR}^2 * \mathrm{TWALL(I)} + \mathrm{TSUR} * \mathrm{TWALL(I)}^2 \\ &+ \mathrm{TWALL(I)}^3) \end{aligned} \tag{16}$$

in which EMIS(I) = the product of emissivity and "view-factor"

and TWALL(I) = effective wall temperature for element I.

For this calculation, both the surface and wall temperatures must be measured in degrees Rankine. The net radiative flux is given by

$$\mathrm{HRAD(I)} * (\mathrm{TSUR} - \mathrm{TWALL(I)}).$$

If one has good values for all of the factors involved in the preceding equations, an exact result is obtained. However, in our problem, the surface temperature is always changing and it is necessary to use an approximate value for TSUR in evaluating HRAD. We recalculate HRAD at each time step. Since the time steps are quite small and the change in HRAD caused by a change in the surface temperature is roughly 1.5 ΔTSUR/TSUR, it is not difficult to keep computational errors well below one percent.

Evaluation of the evaporative component involves several factors. One of the most important, of course, is whether the subject is sweating. Even if he is not, there is still

an evaporative component owing to passive diffusion of water through the skin. In our program it is assumed that the diffusive component is proportional to the difference between the vapor pressure of water at the skin temperature and the partial pressure of water vapor in the ambient air. The proportionality factor is empirically determined. We use the value 6.66 Btu/hr x sq. ft. x psi.

When the subject is actively sweating, the rate at which he produces sweat may determine the rate of evaporation. On the other hand, it is quite common for a subject to produce sweat more rapidly than it can be removed by evaporation. The excess either accumulates on the skin and in the clothing, or it drips off. When the evaporation rate is mass transfer limited, it is proportional to the difference between the partial pressure of water at the surface and in the ambient air. The proportionality factor is a mass transfer coefficient which is determined from dimensionless correlations similar to those used for heat transfer coefficients. When the evaporation rate is multiplied by the latent heat of vaporization, we get the following expression for the maximum rate of heat loss due to evaporation.

EMX = CEVAP * (VPP(TSUR) - VPP(TDEW)) (11)

in which CEVAP = 0.126 * SQRT(VCAB/PCAB) * (TCAB + 460.0) ** 1.04

VCAB = wind speed

PCAB = cabin pressure

TCAB = cabin temperature

VPP(T) = vapor pressure of water
= 0.178 * EXP(9583.0 * (0.0019608 - 1/(T + 460.0)))

TDEW = dew point in the cabin.

There is some question about the exact location about whether evaporation occurs at the skin surface or at the external surface of the garment. This depends on the particular set of circumstances prevailing at the time. The parameter JS(I) specifies the radial node to which the latent heat loss is to be assigned. One should be able to account for

the amount of moisture stored on the skin and in the clothing, but we haven't done it.

The equations defining heat loss to the environment through the respiratory tract have also been changed to conform to the MSC model. It is assumed that expired air leaves the subject saturated with water vapor at a temperature TRES. We have taken

$$TRES = 0.25 * (TA(3) + TV(3)) + 0.5 * TV(1) \qquad (12)$$

According to the MSC control equation for respiration, the volumetric respiration rate is proportional to the total metabolic rate RMET. Hence, the equation defining the rate at which latent heat is removed through the respiratory tract has the form

$$\begin{aligned} QLR = {} & 1040.0 * 0.0418 * RHOG * RMET \\ & * (VPP(TRES) - 0.8 * VPP(TDEW)) \qquad (13) \\ & * 18.0/(29.0 * PCAB) \end{aligned}$$

in which RHOG = density of inspired gas

Similarly, the rate of sensible heat removal is given by

$$QSR = 0.0418 * RHOG * CPGAS * (TRES - TCAB) \qquad (14)$$

One-half of the heat loss through the respiratory tract is assigned equally to the arterial and venous pools in the head, and the remainder is assigned to the venous pool in the chest.

3. Program Organization

The program contains four parts:

(1) Data input
(2) Computation of constant parameters
(3) Transient state computations
(4) Data output

These parts are not completely separated in the program,

but parts 1 and 2 are completed before parts 3 and 4 are begun.

Data Input

Input statements are located near the beginning of the program. All input is from cards. Each READ statement is set off by blank cards preceding and following it. COMMENT cards defining each variable in the READ statement also precede it. Since these cards provide adequate definition of the variables, further discussion will not be included here.

Computation of Constant Parameters

It is necessary to compute a number of intermediate quantities which do not change during the remainder of the calculations. Representative of these computed parameters are the volumes of the annular shells and certain geometric parameters which define the thermal flux between shells in terms of the difference in shell temperatures. The program is arranged so that all of these values are computed before any time dependent quantities are computed. This arrangement reduces the number of calculations that have to be done when physiological parameters, such as blood flow rate, change. These calculations are completed at Statement 505.

Transient State Computations

The calculations for each time step begin at Statement 13 where temperatures to be used in the MSC control equations are identified. Following this step the program procedes to evaluate SWEAT, STRIC, and QSHIV. If none of these quantities has changed more than five percent from the most recently used value, the remaining control equations are skipped and old values of the physiological parameters are retained. Otherwise, new values are computed.

Evaluation of the physiological parameters starts with the calculation of heat generation, blood flow, and

evaporation rates using the MSC control equations. These quantities are then distributed among the regions in our model as discussed earlier. Finally, a check is made to see whether the evaporation rate for any of the elements is mass transfer limited.

Following evaluation of the physiological parameters, another series of intermediate values is calculated. These values are independent of temperature and need not be recalculated as long as the physiological parameters remain constant.

The calculations that must be performed at each time step start at Statement 60 where TRES, the effective respiratory temperature, is evaluated. Following evaluation of the rate of heat loss through the respiratory tract, the calculations required for the simultaneous evaluation of all of the new tissue temperatures are performed. Time is then incremented and a check is made to determine whether the temperatures are to be printed.

After the temperatures have been printed, TIME is checked against TIMELMT. If TIME exceeds TIMELMT, the calculation is terminated in a manner determined by the value of LOOP. The final problem in a series of problems is identified by LOOP = 2. If LOOP = 1 control is transferred to a section of the program where data can be changed in preparation for running another problem.

Data Output

Temperatures can be printed at equally spaced intervals of time as specified by the user. The values at ten radial nodes are printed for each element. These nodes are specified by the ten values of JJ(I,K) read in for each element.

The output is arranged so that temperatures for a given element are printed in two rows, one containing the ten tissue temperatures and the other containing TA, TV, and TE for the element. Identification of each tissue temperature is accomplished by printing the corresponding value of R/A. R is the radial coordinate of the point and A is the radius of the skin. It should be noted that this ratio is greater than unity for points located in clothing.

A heading at the beginning of the printed output identifies the elements, lists the number of radial nodes in each element, and lists the values of A.

All temperatures are printed in degrees Fahrenheit except for the last table in which the values are converted to degrees Centigrade. Radial coordinates in centimeters are also used in the last table.

4. Results - A Comparison with Corresponding Values Calculated Using the MSC Subroutine MAN.

This contract was initiated because of the necessity for checking the validity of the twelve-node model being used at the MSC. The parameters for our model were chosen equal to corresponding parameters in the MSC model. Then a series of problems was run to see whether significant differences between the two models did indeed exist.

Two sets of comparison runs were made, one for a high work rate in a warm environment and one for a low work rate in a cool environment. It was observed that differences between the two models, especially those attributable to truncation errors in the finite difference equations, were more pronounced in the cooling case where rather steep internal temperature gradients were generated. Center to surface temperature differences of 20°F existed at the end of two hours of cooling while differences of 5°F were more typical at the end of the heating period. The exaggerated importance of convective heat transport by circulating blood tended to overshadow completely conductive transport in the heating case.

Table IV contains a summary of the results obtained for the heating problems. The calculations cover a four hour period in real time. During the first two hour period, the work rate is 400 Btu/hr in an 82.4°F environment. The dew point temperature is 70°F. At the end of the two hour initial period, the work rate is increased to 3151 Btu/hr and the ambient dry bulb temperature is increased to 86°F. Computations were performed for the ensuing two hour period. In Table IV, time = 0 denotes the beginning of the second period.

Table IV. Comparison of the Two Models for the Case of Heating

	WORK = 400 TE = 82.4		WORK = 3151 TE = 86.0			
	TIME = 0		TIME = 0.1		TIME = 2.1	
	NASA	MAPS	NASA	MAPS	NASA	MAPS
Head-C	99.09	98.8	100.29	99.1	106.64	106.9
S	94.12	93.6	95.25	93.6	105.54	102.1
Trunk-C	99.57	99.0	100.72	100.5	107.03	107.2
M	99.42	99.6	102.27	100.9	107.77	107.5
S	93.99	94.9	95.20	96.5	105.86	104.2
Arms-M	99.53	99.2	102.36	101.4	105.98	103.6
S	93.31	94.0	97.37	96.6	105.98	103.6
Hands-M	98.10	99.5	98.38	101.4	106.30	107.6
S	97.63	95.5	99.99	97.5	106.55	104.8
Legs-M	99.83	99.5	102.31	101.4	107.68	107.8
S	92.33	91.9	96.00	93.3	105.88	102.5
Feet-M	97.22	98.9	97.37	101.3	104.64	107.8
S	95.61	93.2	97.95	94.3	105.67	102.7
Blood	99.31	98.7	101.66	99.8	106.84	106.5

The initial values are nearly equal to equilibrium values for a man doing light work at 82.4°F., and results obtained using the two models are in reasonable agreement. With the exception of the values for the hands and feet, where there are obvious idfferences between the two models, the difference between two corresponding values is no more than 1°F. Many of the differences are less than 0.5°F.

As the values tabulated for t = 0.1 indicate, somewhat larger differences develop during the initial heating period. The differences associated with core and muscle temperatures

tend to decrease in magnitude during the course of the calculation. At the end of the two hour work period, the largest difference in internal temperature is 0.3°F. However, considerably larger differences do exist between several of the skin temperatures. The MSC model yields skin temperatures for the head, arms, and legs that are 2.3°F. higher than those predicted by our model.

Similar calculations are reported for a cooling situation in which the work rate is held constant at 600 Btu/hr. There is an initial two hour period in which the environmental temperature is held at 82 .4°F. This is followed by a cooling period during which the environmental temperature is 50°F.

The agreement between the two models is not as good in this case as it was in the heating case. Differences at the end of the initial period are comparable in the two cases. However, as cooling progresses, skin temperatures computed using the NASA model fall considerably below corresponding values computed using our model. The difference between the two arm skin temperatures is 7.55°F., which is certainly a significant difference.

Table V. Comparison of the Two Models for the Case of Cooling

	WORK = 600			
	TE = 82.4 TIME = 0		TE = 50.0 TIME = 2.0	
	NASA	MAPS	NASA	MAPS
Head-C	99.16	99.2	97.90	97.4
S	92.90	92.3	81.58	80.9
Trunk-C	99.82	99.2	99.10	97.6
M	99.79	99.4	98.93	97.7
S	92.86	94.1	81.57	86.8
Arms-M	97.90	99.6	98.90	98.2
S	92.19	93.1	74.25	81.8

Table V. (Continued)

	WORK = 600			
	TE = 82.4, TIME = 0		TE = 50.0, TIME = 2.0	
	NASA	MAPS	NASA	MAPS
Hands-M	97.81	99.9	92.54	97.8
S	97.25	94.7	91.18	85.6
Legs-M	100.18	99.8	99.31	98.0
S	91.07	90.8	69.97	74.7
Feet-M	96.68	99.4	90.24	98.0
S	94.59	91.9	84.17	78.3
Blood	99.58	98.9	98.85	97.0

It should be recognized that either of these models contains enough free parameters to permit fitting a limited amount of experimental data with reasonable accuracy. For example, reducing the amount of vasoconstriction occurring in a cold environment would undoubtedly raise the skin temperatures. Similarly, reducing the amount of vasodilatation in a warm environment would lower skin temperatures. If one's primary objective is to develop an engineering model that can be used to predict system performance, no particular physical significance need be attached to the parameters and they can be adjusted as required. On the other hand, if one's objective is to determine values of physiological variables, it is important that the model provide a reasonably accurate representation of the actual physical system. We feel that the results presented in this section indicate that a more detailed model than the NASA model is required for the second purpose.

References

1. E. H. Wissler, A Mathematical Model of the Human Thermal System, Bull. Math. Biophysics, 26, 147-166 (1964).

Appendix A

Reprint of

"A Mathematical Model of the Human Thermal System,"

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A MATHEMATICAL MODEL OF THE HUMAN THERMAL SYSTEM*

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This paper describes a mathematical model developed to simulate the physical characteristics of the human thermal system in the transient state. Physiological parameters, such as local metabolic heat generation rates, local blood flow rates, and rates of sweating, must be specified as input data. Automatic computation of these parameters will be built into the model at a later date when it is used to study thermal regulation in the human.

Finite-difference techniques have been used to solve the heat conduction equation on a Control Data Corporation 1604 computer. Since numerical techniques were used, it was possible to include many more factors in this model than in previous ones. The body was divided into 15 geometric regions, which were the head, the thorax, the abdomen, and the proximal, medial, and distal segments of the arms and legs. Axial gradients in a given segment were neglected. In each segment, the large arteries and veins were approximated by an arterial pool and a venous pool which were distributed radially throughout the segment. Accumulation of heat in the blood of the large arteries and veins, and heat transfer from the large arteries and veins to the surrounding tissue were taken into account. The venous streams were collected together at the heart before flowing into the capillaries of the lungs. Each of the segments was subdivided into 15 radial sections, thereby allowing considerable freedom in the assignment of physical properties such as thermal conductivity and rate of blood flow to the capillaries.

The program has been carefully checked for errors, and it is now being used to analyze some problems of current interest.

The synthesis of an adequate mathematical model for the human thermal system must include the following factors: (1) the manner in which heat generated by metabolic reactions is distributed throughout the body, (2) conduction of

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heat due to thermal gradients, (3) convection of heat by circulating blood, (4) the geometry of the body, (5) the relatively low thermal conductivity of the superficial layer of fat and skin, (6) countercurrent heat exchange between large arteries and veins, (7) heat loss through the respiratory tract, (8) sweating, (9) shivering, (10) the storage of heat, and (11) the condition of the environment, including its temperature, motion relative to the body, and relative humidity. Some of these factors, such as the last one, can be measured with relative ease. On the other hand, such factors as the local rate of heat generation can only be measured *in vivo* with great difficulty, and their values must be deduced from indirect measurements. Indeed, one of the principal uses of a mathematical model is to assign reasonable values to those parameters which cannot be measured directly in an experiment.

Early mathematical models, such as those developed by L. W. Eichna, W. F. Ashe, W. B. Bean, and W. B. Shelley (1945) and by W. Machle and T. F. Hatch (1947) were based on the "core and shell" concept in which the rectal temperature and the mean skin temperature were used as measures of the deep and superficial temperatures, respectively. Since the amount of information built into these models is relatively small, the formulas are simple and easy to use, but they fail in many cases. For instance, D. McK. Kerslake and J. L Waddell (1958) have observed that the relative volumes assigned to the core and shell depend on the peripheral circulation, but these models do not consider this explicitly.

Recent attempts to build more information into the models have involved the use of modern computers of both the analog and digital types. In either case, the basic problem has been to solve the transient-state heat conduction equation with internal heat generation. C. H. Wyndham and A. R. Atkins (1960) have approximated the human by a series of concentric cylinders. Assuming that the rate of heat transfer between adjacent cylinders is proportional to the difference between the temperatures of the cylinders leads to a set of first-order differential equations which are easily solved on an analog computer. The effect of peripheral circulation is implicitly included in the model by allowing the effective thermal conductivity to vary as a function of temperature. R. J. Crosbie, J. D. Hardy, and E. Fessenden (1961) have adopted a very similar approach using an infinite slab rather than a cylinder. They have built in some of the more important physiological responses to thermal stress by allowing the effective thermal conductivity, metabolic rate, and rate of vaporization to vary as the mean temperature of the body varies. Although these models do include, in a not clearly defined mean manner, some of the factors mentioned in the first paragraph, they do not include the effect of regional variations in heat generation rates and blood flow rates. Wyndham and Atkins are currently adapting their model to include regional variations by using a physical system similar to the one discussed below.

In two previous papers, the author has obtained both steady-state (1961a) and transient-state solutions (1961b) for a model based on a representation of the human using six cylindrical elements. Two of the elements represent the arms; two represent the legs; one represents the trunk; and the sixth represents the head. The elements are connected by the vascular system. Each element is a two-region composite cylinder, with the inner region composed of tissue, bone, and viscera and the outer region composed of fat and skin. All of the factors mentioned in the opening paragraph were explicitly included in the analysis, but such variables as local heat generation rates and local blood flow rates were assigned as parameters to be specified in the input data. The solution obtained was an analytical one expressed in terms of an infinite series of orthogonal functions, and a high-speed digital computer was used to evaluate the temperatures for a particular case. Much of the computation time was spent evaluating eigenvalues; and since this had to be repeated whenever a physiological variable changed, the program was not a very efficient one for studying thermal regulation problems in which physiological parameters were varying rapidly. Therefore, it was decided to investigate the possibility of obtaining a more versatile solution by using finite difference techniques. The purpose of this paper is to describe the result of this investigation.

Theory. The physical system on which the equations are based is shown in Figure 1. It consists of a number of cylindrical elements representing longi-

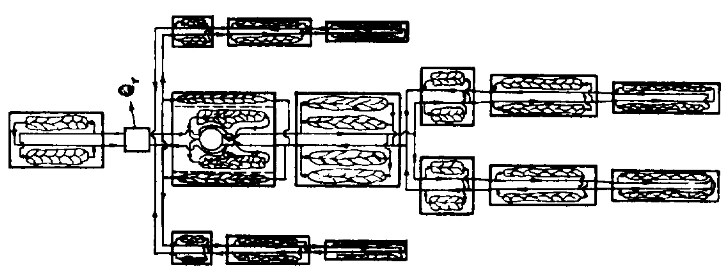

Figure 1. A schematic diagram showing the geometric arrangement of the elements and the circulatory system

tudinal segments of the arms, legs, trunk, and head. Each element, consisting of a conglomeration of tissue, bone, fat, and skin, has a vascular system which can be divided into three subsystems representing the arteries, the veins, and the capillaries. The heat which is generated in the elements by metabolic reactions is either stored in the element, carried away by circulating blood, or conducted to the surface where it is transferred to the environment. This is simply a statement of the first law of thermodynamics, which can be formulated mathematically as the heat conduction equation given below:

$$(\rho C_i)\frac{\delta T_i}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r}\left(k_i r\frac{\delta T_i}{\delta r}\right) + h_{mi} + Q_{ci}(T_{ai} - T_i) + H_{ai}(T_{ai} - T_i) + H_{vi}(T_{vi} - T_i), \quad (1)$$

in which

$T_i(t, r)$ = instantaneous temperature of the tissue, bone, or viscera at a distance r from the axis of the ith element,
$\rho_i(r)$ = density of tissue,
$C_i(r)$ = specific heat of tissue,
$k_i(r)$ = effective thermal conductivity of tissue,
$h_{mi}(t, r)$ = metabolic heat generation per unit volume,
$Q_{ci}(t, r)$ = product of the mass flow-rate and specific heat of blood entering the capillary beds per unit volume,
$H_{ai}(t, r)$ = heat transfer coefficient between the arteries and tissue per unit volume,
$H_{vi}(t, r)$ = heat transfer coefficient between the veins and tissue per unit volume,
$T_{ai}(t)$ = temperature of the arterial blood,
$T_{vi}(t)$ = temperature of the venous blood.

The term on the left-hand side of equation (1) is the rate of accumulation of thermal energy per unit volume due to the changing temperature of the tissue and capillary blood in the volume. This equals the sum of the five terms on the right which represent in order the net rate of conduction of heat into a unit volume, the rate of heat generation by metabolic reactions, the net rate at which heat is carried into the volume by capillary blood, the rate at which heat is transferred from arterial blood to the tissue, and the rate at which heat is transferred from venous blood to the tissue. It should be observed that this form of the heat conduction equation is applicable only to an axially symmetrical system in which the longitudinal conduction of heat is negligible. This means that the analysis does not apply to situations in which the subject is curled up in a ball in order to conserve heat. If the subject is moving so that there is a uniform flow of air around each of the elements, the analysis should apply. H. H. Pennes (1948) has shown that longitudinal conduction in the arms is relatively unimportant. This should be true also in the legs, but probably is not true in the head. It has been assumed that there is perfect heat transfer between the blood in the capillaries and the neighboring tissue, i.e., the temperature of blood leaving the capillary beds is equal to the temperature of the neighboring tissue. Because of the small diameter of the capillaries this is probably a good approximation, but such a simple condition does not prevail in the larger vessels. As a first approximation it has been assumed in this paper that the rate of heat transfer from the blood in the large vessels to the neighboring tissue is proportional to the difference between the blood and tissue temperatures. The proportionality factor has been called H_a for the arteries and H_v for the veins.

Since the temperature of blood in the large vessels changes with time, it is necessary to write two more thermal energy balances. In formulating the equation for the arteries it has been assumed that the arteries in the ith element form a pool having a uniform temperature, T_{ai}. The rate of accumulation of the thermal energy in this reservoir is equal to the sum of the net rate at which heat is carried into the pool by flowing blood, the rate at which heat is transferred from neighboring tissue to the blood in the pool, and the rate at which heat is transferred directly from the venous pool to the arterial pool due to the proximity of certain arteries and veins. This equality is expressed mathematically in the following equation.

$$(MC)_{ai}\frac{\delta T_{ai}}{\delta t} = Q_{ai}(T_{am} - T_{ai}) + 2\pi L_i\int_0^{a_i} H_{ai}(T_i - T_{ai})r\,dr + H_{avi}(T_{vi} - T_{ai}), \quad (2)$$

in which

$T_{am}(t)$ = temperature of the blood entering the arterial pool,
M_{ai} = mass of the blood contained in the arterial pool of the ith element,
C_{ai} = specific heat of blood,
$Q_{ai}(t)$ = product of the mass flow rate and specific heat for blood entering the arterial pool,
L_i = length of the ith element,
H_{avi} = heat transfer coefficient for direct transfer between large arteries and veins.

The integral is necessary in equation (2) because the tissue temperature is a function of r.

The corresponding equation for the venous pool is

$$(MC)_{vi}\frac{\delta T_{vi}}{\delta t} = Q_{vi}(T_{vn} - T_{vi}) + 2\pi L_i\int_0^{a_i} (Q_{ci} + H_{vi})(T_i - T_{vi})r\,dr + H_{avi}(T_{ai} - T_{vi}), \quad (3)$$

in which

$Q_{vi}(t)$ = product of mass and specific heat for venous blood flowing into the venous pool of the ith element from the nth element.

It will be assumed throughout this analysis that the M_{ai}'s and M_{vi}'s are constants so that

$$Q_{ai}(t) = Q_{vi}(t) + 2\pi L_i \int_0^{a_i} Q_{ci}(t, r) r dr. \tag{4}$$

The equation for the venous temperature in the abdominal section is slightly different than equation (3) because two veins, one from each leg, flow into this section. It was also necessary to modify the equations for the thoracic section since all of the venous streams terminate and the arterial streams originate in this section. It was assumed that the temperature of the blood entering the pulmonary capillaries is equal to the "cup mixing" mean temperature of the venous streams entering the right ventricle. This necessitated a change in equation (1) because the temperature of the venous blood entering the pulmonary capillaries is different than the temperature of the arterial blood entering the more superficial capillaries of the thorax:

$$(\rho C)_1 \frac{\delta T_1}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r}\left(k_1 r \frac{\delta T_1}{\delta r}\right) + h_{m1} + Q_{ca}(T_{a1} - T_1) + Q_{cv}(T_{v1} - T_1) + H_{a1}(T_{a1} - T_1) + H_{v1}(T_{v1} - T_1), \tag{5}$$

in which

$Q_{ca}(t, r)$ = product of the mass flow rate and specific heat for arterial blood flowing into the capillaries,

$Q_{cv}(t, r)$ = product of the mass flow rate and specific heat for venous blood flowing into the pulmonary capillaries.

Equations (2) and (3) were also modified to take cognizance of the fact that venous blood flows into the pulmonary capillaries which in turn empty into the arterial pool:

$$(MC)_{a1} \frac{\delta T_{a1}}{\delta t} = 2\pi L_1 \int_0^{a_1} Q_{cv}(T_1 - T_{a1}) r dr + 2\pi L_1 \int_0^{a_1} H_{a1}(T_1 - T_{a1}) r dr + H_{av1}(T_{v1} - T_{a1}) \tag{6}$$

$$(MC)_{v1} \frac{\delta T_{v1}}{\delta t} = \sum_i Q_{v1i}(T_{vi} - T_{v1}) + 2\pi L_1 \int_0^{a_1} H_{vi}(T_1 - T_{v1}) r dr + H_{av1}(T_{a1} - T_{v1}) + q_{rv1}, \tag{7}$$

in which

$q_{rv1}(t)$ = rate at which heat is transferred from venous blood in the thorax to air in the respiratory tract,

$Q_{v1i}(t)$ = rate at which venous blood flows from the *ith* element into the venous pool in the thorax $= Q_{ai}(t)$ for those elements which are connected to the thoracic segment.

The total rate of heat loss through the respiratory tract depends on the respiratory rate and the temperature and humidity of the inspired air. In this analysis it was assumed that the expired air was saturated with water vapor at a mean temperature T_r:

$$T_r = 0.25T_{v-\text{head}} + 0.25T_{a-\text{head}} + 0.5T_{v-\text{chest}}. \tag{8}$$

Furthermore, it was assumed that 25 per cent of the heat loss through the respiratory tract came from the arterial pool in the head, 25 per cent from the venous pool in the head, and 50 per cent from the venous pool in the thorax.

Before these equations can be solved uniquely, certain constraining conditions must be specified. Some of these take the form of initial conditions, which specify all of the temperatures at the instant the transient begins:

$$T_i(0, r) = T_{0i}(r) \tag{9}$$

$$T_{ai}(0) = T_{a0i} \tag{10}$$

$$T_{vi}(0) = T_{v0i}. \tag{11}$$

Also needed are boundary conditions which relate the subject to his environment. In general they are based on the fact that the local rate of conduction of heat to the surface through the tissue is equal to the rate of heat transfer from the surface to the environment:

$$-\left[k_i \frac{\delta T_i}{\delta r}\right]_{r=a_i} = H_i[T_i(t, a_i) - T_{ei}], \tag{12}$$

in which

H_i = heat transfer coefficient,
T_{ei} = effective environmental temperature.

The heat transfer coefficient depends on the physical properties of the fluid surrounding the element, the velocity of the fluid, the wetness of the surface, and the relative humidity of the environment. If heat transfer by evaporation is important, the effective temperature of the environment will be lower than the dry-bulb temperature. In this paper, the heat transfer coefficient for a subject in air has been computed using the equation

$$H_i = H_{ci} + H_{ri} + \lambda_i \left(\frac{dp}{dT}\right)_i (K_i F_i + K_{Di}), \tag{13}$$

in which

H_{ci} = heat transfer coefficient for convection,
H_{ri} = heat transfer coefficient for radiation,

λ_i = latent heat of water at T_i,
$(dp/dT)_i$ = rate of change of partial pressure of water with temperature at T_i,
K_i = mass transfer coefficient for convection,
F_i = wetted fraction of the surface,
K_{Di} = mass transfer coefficient for passive diffusion of water through the epidermis.

A summary of the equations used has been published previously (Wissler, 1961a). Finally, since each element possesses axial symmetry,

$$\left(\frac{\delta T_i}{\delta r}\right)_{r=0} = 0. \tag{14}$$

Solution of the equations. The use of numerical techniques and large, high-speed digital computers to solve the heat conduction equation has received considerable attention lately. A good description of these techniques is given in the recent book by G. E. Forsythe and R. W. Wasow (1960). The principal feature of finite-difference techniques is that they can be used even if the physical properties vary with position, and it is for this reason that they were employed to solve the equations presented in the preceding section.

Basically, the procedure used consists of subdividing each of the circular elements into a number of annular shells and assigning a single characteristic temperature to the material in each of the shells. Then the right-hand side of equation (1) at a particular value of r can be approximated by a linear algebraic equation. Furthermore, no attempt is made to compute the temperatures of the shells as continuous functions of time. Instead, one employs a marching procedure in which the initial temperatures are used to compute the temperatures a short interval of time, Δt, later. These new temperatures are then used to compute the temperatures at time, $2\Delta t$, and so on as long as necessary.

Figure 2 is helpful in visualizing this process. Normally, the temperatures in a given element are all specified at $t = 0$, the row $k = 1$, by the initial conditions; and the problem is to devise a procedure for computing temperatures in the next row ($k = 2$), and so forth until the entire table has been completed. It should be noted that the space and time steps need not all be the same size. One can use small space steps near the outside of the cylinder where the temperature gradients are the largest and large space steps near the center where the temperature gradients are small. Similarly, small time intervals can be used at the beginning of the interval when the temperature is changing rapidly, and larger time intervals can be used near the end of the transient.

In the development of the finite-difference equations, we will let $T_{i,kj}$ be the temperature existing at the jth radial point r_j, in the ith element after the $(k-1)$th time step, $t = t_k$. The difference equation used to approximate equation (1) was obtained by integrating each term in the equation over an annular region ranging from $r = r_j - (h_-/2)$ to $r = r_j + (h_+/2)$, in which h_-

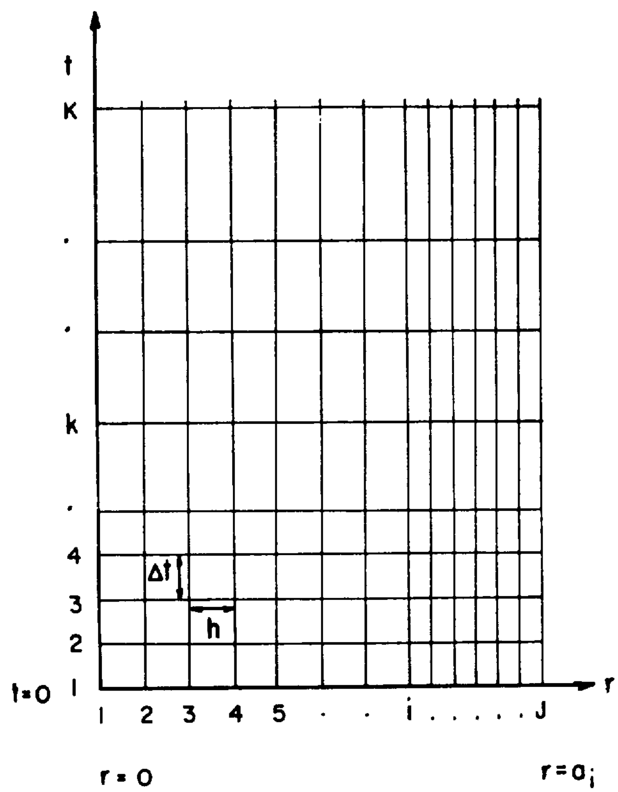

Figure 2. Diagram showing the temporal and spacial steps used in deriving the finite difference equations

is the space increment to the left of r_j and h_+ is the increment to the right of r_j. Assuming that $T_{i,kj}$ is characteristic of the temperature in this interval and allowing the physical properties to have one value (subscript $-$) to the left of r_j and another value (subscript $+$) to the right of r_j, one obtains the following equation:

$$\left[\frac{h_-(r_j - h_-/4)}{2}(\rho C)_{i-} + \frac{h_+(r_j + h_+/4)}{2}(\rho C)_{i+}\right]\frac{\delta T_{i,kj}}{\delta t} \cong$$

$$k_{i+}(r_j + h_+/2)\frac{\delta T_{i,k(j+1/2)}}{\delta r} - k_{i-}(r_j - h_-/2)\frac{\delta T_{i,k(j-1/2)}}{\delta r} +$$
$$\Big\{\frac{h_-(r_j - h_-/4}{2}[(Q_{ci-} + H_{ai-})(T_{ai,k} - T_{i,kj}) + H_{vi-}(T_{vi,k} - T_{i,kj})] +$$
$$\frac{h_+(r_j + h_+/4)}{2}[(Q_{ci+} + H_{ai+})(T_{ai,k} - T_{i,kj}) + H_{vi+}(T_{vi,k} - T_{i,kj})]\Big\}. \quad (15)$$

A common factor of 2π has been cancelled out of each term. Similarly, integrating over the interval from $r_J - h_-/2$ to r_J and using equation (12) to evaluate $[k_{i-}(\delta T/\delta r)]_{r=r_J}$, one obtains

$$h_-(r_J - h_-/4)(\rho C)_{i-}\frac{\delta T_{i,kJ}}{\delta t} \cong -k_{i-}(r_J - h_-/2)\frac{\delta T_{i,k(J-1/2)}}{\delta r} -$$
$$r_J H_i(T_{i,kJ} - T_{ei}) +$$
$$\frac{h_-(r_J - h_-/4)}{2}[(Q_{ci} + H_{ai-})(T_{ai,k} - T_{i,kJ}) +$$
$$H_{vi-}(T_{vi,k} - T_{i,kJ})]. \quad (16)$$

The derivatives appearing in the preceding equations are approximated as follows:

$$\frac{\delta T_{i,(k+1/2)j}}{\delta t} = \frac{T_{i,(k+1)j} - T_{i,kj}}{\Delta t} \quad (17)$$

$$\frac{\delta T_{i,k(j+1/2)}}{\delta r} = \frac{T_{i,k(j+1)} - T_{i,kj}}{\Delta r} \quad (18)$$

$$\frac{\delta T_{i,k(j-1/2)}}{\delta r} = \frac{T_{i,kj} - T_{i,k(j-1)}}{\Delta r}. \quad (19)$$

Substituting the preceding expressions into equations (15) and (16) and using the arithmetic mean of the values of the right-hand side at times t_k and t_{k+1} to approximate the value of the right-hand side at time $(t_k + t_{k+1})/2$, one obtains a set of equations each having the form

$$A_{i,j}T_{i,(k+1)(j-1)} + B_{i,j}T_{i,(k+1)j} + C_{i,j}T_{i,(k+1)(j+1)} +$$
$$U_{i,j}T_{ai,k+1} + V_{i,j}T_{vi,k+1} = D_{i,j}, \quad (20)$$

in which $A_{i,j}$, $B_{i,j}$, $C_{i,j}$, $U_{i,j}$, and $V_{i,j}$ are constants determined by the physical properties and the mesh size, and $D_{i,j}$ is determined by the temperatures at time t_k. It is worth noting that $A_{i,1}$ and $C_{i,J}$ are both zero.

Equation (2) was next approximated in the following way. In place of the derivative on the left-hand side use

$$\frac{\delta T_{ai,(k+1/2)}}{\delta t} = \frac{T_{ai,k+1} - T_{ai,k}}{\Delta t}, \quad (21)$$

and in place of the integral containing T_i use

$$\int_0^{a_i} H_{ai}(r)T_i(t_k, r)rdr \cong \sum_{j=1}^{J} W_{i,j}T_{i,kj}, \tag{22}$$

in which

$$W_{i,j} = \int_{r_j - h_-/2}^{r_j + h_+/2} H_{ai}(r)rdr. \tag{23}$$

Substituting the expressions given in equations (22) and (23) into equation (2) and again using the mean of the values of the right-hand side at times t_k and t_{k+1}, one obtains an equation having the form

$$\sum_{j=1}^{J} W_{i,j}T_{i,(k+1)j} + U_{i,J}T_{ai,k+1} + V_{i,J}T_{vi,k+1} = D_{i,J} + E_{i,J}T_{am,k+1}. \tag{24}$$

Similarly, equation (3) can be approximated by an algebraic equation having the form

$$\sum_{j=1}^{J} X_{i,j}T_{i,(k+1)j} + U_{i,J+1}T_{ai,k+1} + V_{i,J+1}T_{vi,k+1} = D_{i,J+1} + E_{i,J+1}T_{vn,k+1}. \tag{25}$$

Given the temperatures $T_{am,k+1}$ and $T_{vn,k+1}$ of the arterial and venous blood entering an element, one can compute the tissue temperatures and blood temperatures in that element by solving simultaneously the J equations represented by equation (19) together with equations (24) and (25). Because of the particularly simple form of equation (20), a solution can be obtained with ease using a Gaussian elimination procedure. The complete set of equations is displayed below:

$$\begin{array}{ll}
B_1T_1 + C_1T_2 & + U_1T_a + V_1T_v = D_1 \\
A_2T_1 + B_2T_2 + C_2T_3 & + U_2T_a + V_2T_v = D_2 \\
\qquad A_3T_2 + B_3T_3 + C_3T_4 & + U_3T_a + V_3T_v = D_3 \\
\cdots & \cdots \\
A_{J-2}T_{J-3} + & \\
\qquad B_{J-2}T_{J-2} + C_{J-2}T_{J-1} & + U_{J-2}T_a + V_{J-2}T_v = D_{J-2} \\
\qquad A_{J-1}T_{J-2} + B_{J-1}T_{J-1} + C_{J-1}T_J & + U_{J-1}T_a + V_{J-1}T_v = D_{J-1} \\
\qquad\qquad A_JT_{J-1} + B_JT_J & + U_JT_a + V_JT_v = D_J \\
W_1T_1 + W_2T_2 + \cdots + W_{J-1}T_{J-1} + W_JT_J & + U_{J+1}T_a + V_{J+1}T_v = D_{J+1} + E_{J+1}T_{am}
\end{array} \tag{26}$$

$$X_1T_1 + X_2T_2 + \cdots + X_{J-1}T_{J-1} + X_JT_J \quad + U_{J+2}T_a + V_{J+2}T_v = D_{J+2} + E_{J+2}T_{vn}.$$

The subscripts i and $k + 1$ have been dropped to conserve space. To solve this set of equations let

$$b_1 = \frac{C_1}{B_1}, \quad u_1 = \frac{U_1}{B_1}, \quad v_1 = \frac{V_1}{B_1}, \quad q_1 = \frac{D_1}{B_1}, \quad w_1 = W_1, \quad x_1 = X_1,$$

$$b_i = \frac{C_i}{B_i - A_ib_{i-1}}, \quad u_i = \frac{U_i}{B_i - A_ib_{i-1}}, \quad v_i = \frac{V_i}{B_i - A_ib_{i-1}},$$

$$q_i = \frac{D_i}{B_i - A_ib_{i-1}}, \qquad (1 < i \le J)$$

$$w_i = W_i - w_{i-1}b_{i-1} \qquad x_i = X_i - x_{i-1}b_{i-1} \tag{27}$$

$$u_{J+1} = U_{J+1} - \sum_{i=1}^{J} w_iu_i \qquad u_{J+2} = U_{J+2} - \sum_{i=1}^{J} x_iu_i$$

$$v_{J+1} = V_{J+1} - \sum_{i=1}^{J} w_iv_i \qquad v_{J+2} = V_{J+2} - \sum_{i=1}^{J} x_iv_i$$

$$q_{J+1} = D_{J+1} - \sum_{i=1}^{J} w_iq_i \qquad q_{J+2} = D_{J+2} - \sum_{i=1}^{J} x_iv_i.$$

This reduces the set of equations (26) to the simpler set given below:

$$\begin{aligned}
T_1 + b_1T_2 \qquad\qquad\qquad & + u_1T_a + v_1T_v = q_1 \\
T_2 + b_2T_3 \qquad\qquad & + u_2T_a + v_2T_v = q_2 \\
T_{J-1} + b_{J-1}T_J + \qquad & \\
& u_{J-1}T_a + v_{J-1}T_v = q_{J-1} \\
& T_J + u_JT_a + v_JT_v = q_J \\
& u_{J+1}T_a = v_{J+1}T_v = q_{J+1} + E_{J+1}T_{am} \\
& u_{J+2}T_a + v_{J+2}T_v = q_{J+2} + E_{J+2}T_{vn}.
\end{aligned} \tag{28}$$

Now the method of solution in a given element is clear. One solves the last two equations for T_a and T_v, and then computes

$$\begin{aligned}
T_J &= q_J - u_JT_a - v_JT_v \\
T_j &= q_j - b_jT_{j+1} - u_jT_a - v_jT_v, \quad j = J - 1, \ldots, 1.
\end{aligned} \tag{29}$$

Finally, we must devise a scheme for computing simultaneously the blood temperatures in all of the elements. These temperatures are defined by pairs of equations similar to the last two of equations (28). To see how these equations can be solved easily, consider the distal and medial segments of an arm or leg as shown in Figure 3. The equations for these two segments are written below:

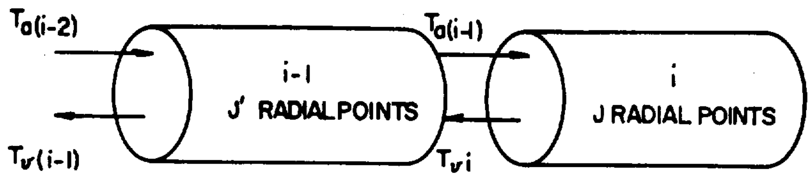

Figure 3. Diagram showing the blood flows into and out of two adjacent elements

$$u_{i-1,\,J'+1}T_{a(i-1)} + v_{i-1,\,J'+1}T_{v(i-1)} = q_{J'+1} + E_{J'+1}T_{a(i-2)} \qquad (30)$$
$$u_{i-1,\,J'+2}T_{a(i-1)} + v_{i-1,\,J'+2}T_{v(i-1)} = q_{J'+2} + E_{J'+2}T_{vi}$$

$$u_{i,\,J+1}T_{ai} + v_{i,\,J+1}T_{vi} = q_{J+1} + E_{J+1}T_{a(i-1)} \qquad (31)$$
$$u_{i,\,J+2}T_{ai} + v_{i,\,J+2}T_{vi} = q_{J+2}.$$

Note that $E_{J+2} = 0$ because there is no venous flow into a distal element. Eliminate T_{ai} from the second of equations (31) to obtain

$$T_{vi} = g_i + S_i T_{a(i-1)}, \qquad (32)$$

in which

$$g_i = \frac{1}{d}\left(\frac{q_{J+1}}{u_{i,\,J+1}} - \frac{q_{J+2}}{u_{i,\,J+2}}\right)$$
$$S_i = \frac{1}{d}\left(\frac{E_{J+1}}{u_{i,\,J+1}}\right)$$
$$d = \frac{v_{i,\,J+1}}{u_{i,\,J+1}} - \frac{v_{i,\,J+2}}{u_{i,\,J+2}}.$$

Substituting the expression for T_{v1} computed in equation (32) into the second of equations (30), one obtains

$$(u_{i-1,\,J'+1} - S_i E_{J'+1})T_{a(i-1)} + v_{i-1,\,J'+1}T_{v(i-1)} = q_{J'+1} + S_i E_{J'+1}. \quad (33)$$

Since this equation has the same form as the second of equations (31), one can obviously obtain another equation of the form

$$T_{v(i-1)} = g_{i-1} + S_{i-1}T_{a(i-2)}. \qquad (34)$$

In this way one can work his way back to the thoracic section where all venous streams terminate and all arterial streams originate. The last two of equations (28) written for the thoracic section have the form

$$u_{1,\,J}T_{a1} + v_{1,\,J}T_{v1} = q_J$$
$$u_{1,\,J+1}T_{a1} + v_{1,\,J+1}T_{v1} = q_{J+1} + \sum_n E_{J+1,\,n}T_{vn}, \qquad (35)$$

in which the summation extends over those elements connected to the thoracic segment. For each of these segments an equation corresponding to equation (34) can be written:

$$T_{vn} = g_n + S_n T_{a1}. \tag{36}$$

Thus, T_{a1} and T_{v1} can be computed using equations (35) and (36), and then all of the remaining temperatures can be computed.

A program was written in Fortran language for performing the previously described calculations on the CDC 1604 computer located at The University of Texas. Since the numerical procedure used only gives an approximate answer and since it is easy to make mechanical mistakes in preparing a program of this size, a great deal of effort was devoted to checking the accuracy of the results.

One good test of the accuracy is to solve a problem for which an analytical solution can be obtained and compare the two results. The distal segment of an arm or leg can be caused to cool like a section of an infinite homogeneous cylinder by setting the rate of blood flow into the segment equal to some negligibly small value (zero leads to division by zero in the program) and setting the metabolic heat generation rate equal to zero. The analytical solution for this case is discussed in many books, such as the one by H. I. Carslaw and J. C. Jaeger (1959). In the test calculation, a uniform initial temperature of 37°C and an environmental temperature of 20°C were used. The physical properties were such that the surface temperature of the cylinder fell to about 24°C during 3,000 seconds of cooling. After 1,000 seconds of cooling, the analytical solution gave a surface temperature of 25.57°C while the numerical solution gave 25.58°C; and after 3,000 seconds of cooling the corresponding temperatures were 24.07°C and 24.06°C. The mean tissue temperature at t = 3,000 seconds computed analytically was 27.81°C while the numerically computed temperature of the venous blood leaving the element, which should be very close to the mean tissue temperature, was 27.84°C. It appears that the numerical procedure used is sufficiently accurate to produce useful results. The above results were obtained using 15 radial points and taking time steps of 5 seconds. Under these conditions, computing the temperatures in all 15 elements of the body requires about 15 minutes of computer time.

Since it is not convenient to obtain analytical solutions for the heat conduction equation applied to a nonhomogeneous cylinder, some other checking procedure had to be devised. It proved to be fairly convenient (and informative since several errors were found in this way) to check the over-all energy balances. For instance, in a given element the net rate at which heat is transported into the element by circulating blood, plus the rate of heat generation by metabolic reactions, minus the rate at which heat is lost to the environment must equal the rate of accumulation of heat in the element. It must also be true that the rate at which heat is carried into the arterial pool in an element by incoming arterial blood, minus the rate at which it is carried out of the pool by arterial blood entering the capillaries or flowing into an adjacent element must equal the rate at which heat is transferred from the arterial pool to the surrounding tissue plus the rate of accumulation of heat in the arterial pool. Making such over-all checks on the computed results indicated that the program was quite free from error.

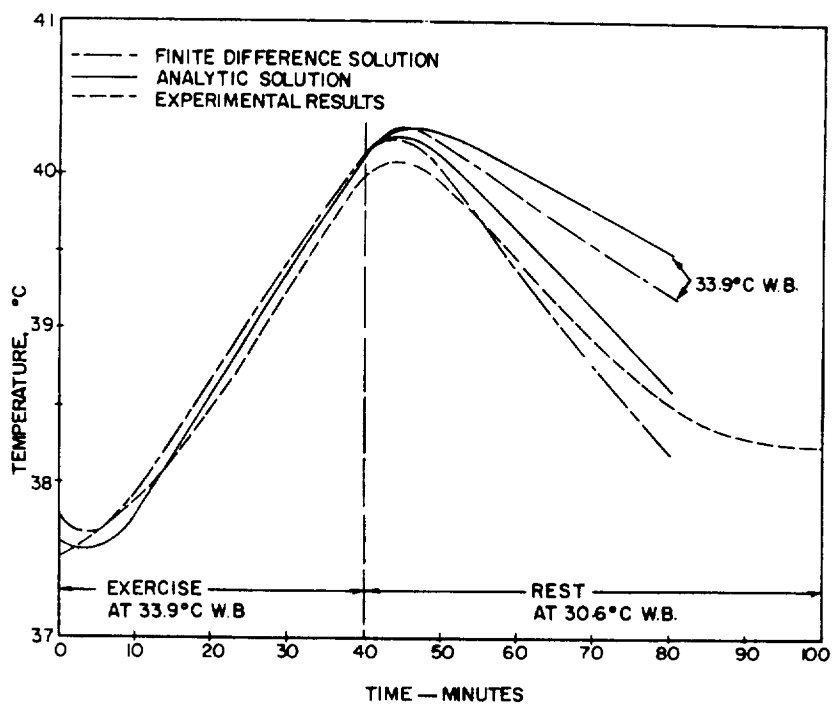

Figure 4. Comparison of rectal temperatures obtained (1) experimentally, (2) by computation using an analytical solution, and (3) by computation using the finite difference scheme presented in this paper

Finally, results computed using the numerical procedure were compared with roughly equivalent results computed using the analytical procedure reported in a previously published paper (Wissler, 1961b). Although inherent differences in the two programs precluded making an exact check, the agreement as shown in Figure 4 was acceptable in the sense that the differences between corresponding curves could be explained logically. The most striking difference is that the central abdominal temperature computed numerically falls much more rapidly during the early resting period than the corresponding temperature computed using the analytical procedure. An explanation for this can be found by studying the temperature profiles existing at the beginning

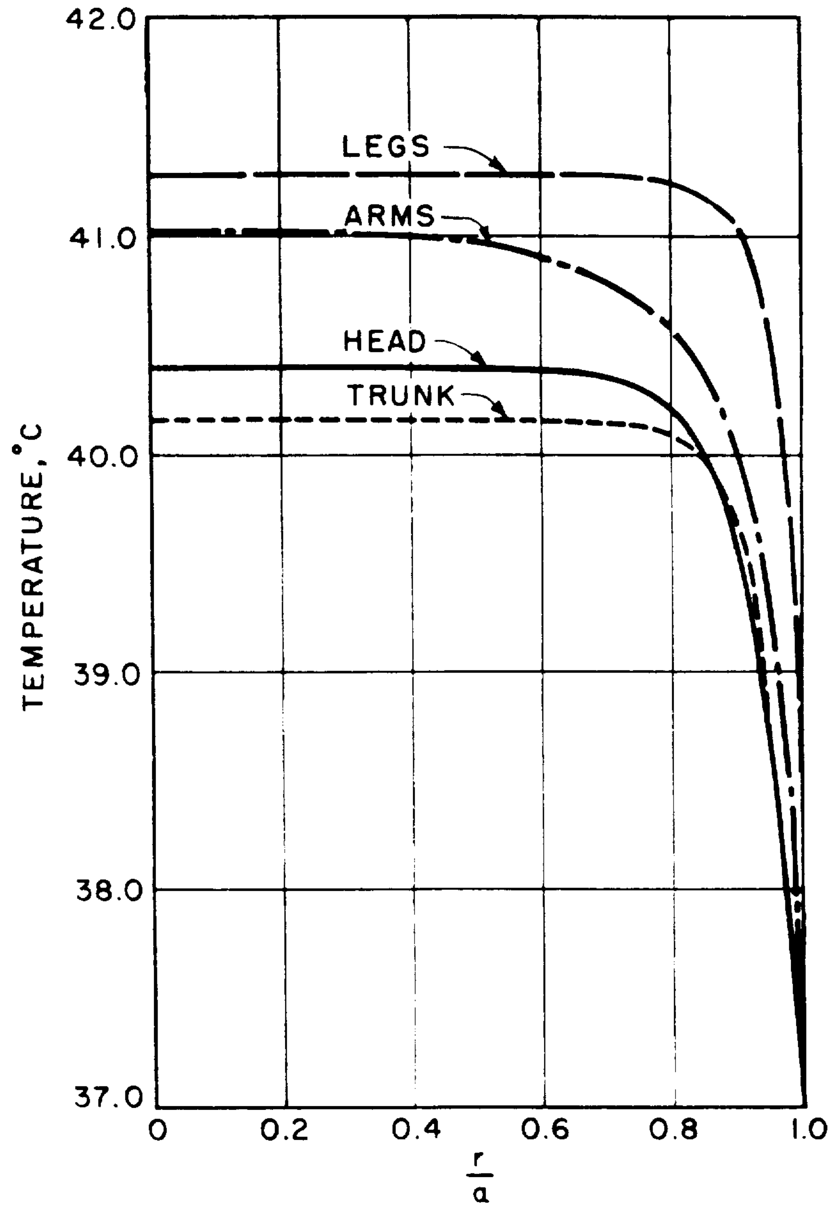

Figure 5. Temperature profiles existing at the end of the exercise period as computed using the analytical solution

of the period of cooling as shown in Figures 5 and 6. One interesting feature is that the mean temperature of the abdomen computed numerically is higher than the corresponding temperature computed using the earlier analytical

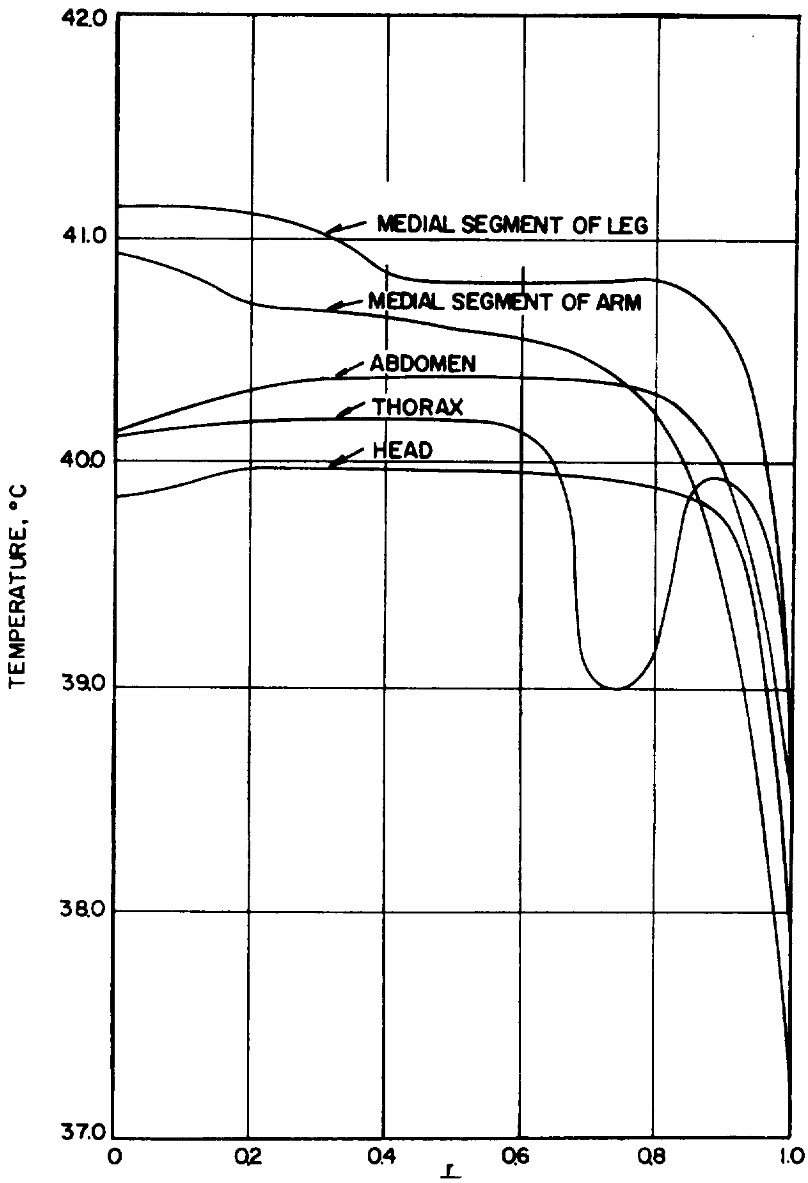

Figure 6. Temperature profiles existing at the end of the exercise period as computed using the finite difference sc heme

solution. This is reasonable because the metabolic heat generated in the trunk was concentrated in the abdomen in the latest model but was distributed uniformly throughout the entire trunk in the earlier model. Although there is not much heat generation in the thoracic section, the temperature is still relatively high. This is due to the very high blood flow rate that exists in the lungs. The pronounced dip in the temperature profile of the thorax occurs in the region just outside of the lungs where a capillary blood flow rate of 0.0004 cc of blood/cc of tissue-second was used. Since this value is much lower than the value of 0.0055 assigned to the subcutaneous region, the temperature of the region just outside of the lungs does not rise as rapidly as the temperature of the lungs or the subcutaneous tissue. Finally, it should be noted that the temperatures of the arms and legs are somewhat lower in the latest model than they were in the previous model. This is due to the fact that the temperature of the arterial blood entering these regions is lower in the latest model. It seems

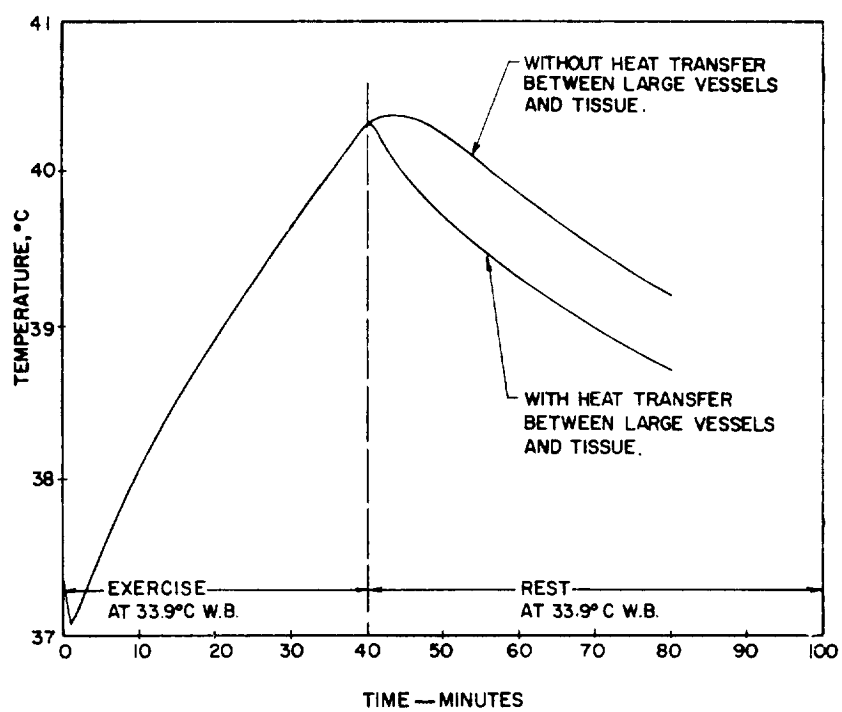

Figure 7. Two curves which show the influence of heat transfer between the blood in large vessels and the surrounding tissue on the rectal temperature during cooling

reasonable that this, in turn, can be attributed to the higher blood flow rates used in the abdomen and thorax. After all, the amount of heat generated in the entire body during the period of exercise is very nearly the same in the two models; and since the abdominal temperature increases more rapidly in the latest model than in the previous model, the temperatures of the extremities must increase less rapidly. Finally, to return to the original point, one would expect the central abdominal temperature computed using the latest model to decrease more rapidly during the first part of the cooling period because the abdominal region is at a higher temperature and, therefore, more susceptible to heat loss than it was when the earlier model was used. This is particularly true because the peripheral regions are at a lower temperature than previously and, hence, they serve as heat sinks.

It was found using the earlier model that allowing heat transfer between adjacent large arteries and veins did not affect the rate of heating or cooling significantly because of the very large blood flow rates used (Wissler, 1961b). In contrast, it was found in this study that permitting heat transfer between the large arteries and veins and the surrounding tissue does have a pronounced effect on the rate of heating or cooling. This is illustrated in Figure 7 where there are presented two cooling curves, one obtained with no heat transfer between the large vessels and tissue and the other obtained with what was evidently too much heat transfer. It is hoped that observations of this kind can be used to determine appropriate values for those parameters which cannot be measured directly.

It is felt that this model contains as much information as the currently available experimental data warrant. The next task is to study the characteristics of the model in order to determine what kind of experiments might be useful in determining those parameters which cannot be measured directly. For example, one can ask whether useful information can be obtained by the measurement of transient temperatures in the brachial veins during periodic heating of a distal portion of the arm. If the calculations show that measurable variations should exist, then a measurement of the amplitude and phase of the variations should prove to be very worth-while. The results of such calculations will be reported in future papers.

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Appendix B

Listing for Program MEM

and Required Data

```
      PROGRAM MEM(INPUT, OUTPUT, PUNCH)
      DIMENSION JH(15,5), JB(15), H(15,5), VOLM(15,21), VOLP(15,21), VOL
     1(15,21), GRADM(15,21), GRADP(15,21), W1M(15,21), W2M(15,21), W3M(1
     25,21), W1P(15,21), W2P(15,21), W3P(15,21), JJ(15,10)
      DIMENSION IFIRST(6), NO(6), GZ(5,6), SZ(5,6), CRP(15)
      DIMENSION TA(15), TV(15), T(15,21), TE(15), TP(15,20)
      DIMENSION JP(15,5), RCT(15,5), RCA(15,5), RCV(15,5), XK(15,5), HME
     1T(15,5), QC(15,5), QCV(5), XL(15), HAT(15,5), HVT(15,5), WA(15,21)
     2, WV(15,21), AERC(15), VERC(15), AQ(15), VQ(15), VQC(15), AEH2(15)
     3, VEH3(15), AR(15,21), BR(15,21), CR(15,21), DHMET(15,21), DA(15,2
     41), DV(15,21), A1(15), A(15), AJBM1(15), AJBM2(15), SMLAR(15,21),
     5SMLBR(15,21), SMLCR(15,21), AEHT(15), VEHT(15), Q(21), AEHTP(15),
     6VEHTP(15), HTC(15), DPDT(15), XLAT(15), XMK(15), FW(15), XMD(15)
      DIMENSION WAE(15), WVE(15), DAA(15), DAV(15), DVA(15), DVV(15), DA
     1C(15), DVC(15), DAAP(15), DVVP(15), WAT(15,21), WVT(15,21), P(6)
      DIMENSION QMET(15), BF(15), RB(15)
      DIMENSION TS(15), TSET(15), WARM(15), COLD(15), QSWEAT(15), EV(15)
      DIMENSION RAD(15,10), RS(15), JS(15)
      DIMENSION RSW(15),AS(15),ARAD(15),EMIS(15),HRAD(15),TWALL(15)
      DIMENSION VCUM(15,5),LV1(15,5),LV2(15,5),CV1(15,5),CV2(15,5)
      COMMON JH, JB, H, VOLM, VOLP, VOL, GRADM, GRADP, W1M, W2M, W3M, W1
     1P, W2P, W3P, JJ, IFIRST, NO, GZ, SZ, TA, TV, T, TE, JP, RCT, RCA,
     2RCV, XK, HMET, CRP, QC, QCV, HAT, HVT, WA, WV, AERC, VERC, AQ, VQ,
     3 VQC, AEH2, VEH3, AR, BR, CR, XL, DHMET, DA, DV, A1, A, AJBM1, AJB
     4M2, SMLAR, SMLBR, SMLCR, AEHT, VEHT, HTC, DPDT, XLAT, XMK, FW, XMD
     5, WAE, WVE, DAA, DAV, DVA, DVV, DAC, DVC, DAAP, DVVP, WAT, WVT, P
      PRINT 102
C
 1    READ 103
C
      PRINT 103
      PRINT 104
      PRINT 105
C
C     UNITS USED ARE BTU'S, DEGREES FAHRENHEIT,FEET,HOURS,AND POUNDS MASS
C     PCAB = CABIN PRESSURE, TCAB = CABIN TEMPERATURE
C     TDEW = CABIN DEW POINT, RHOG = AIR DENSITY
C     CPGAS = SPECIFIC HEAT OF AIR, VCAB = CABIN AIR VELOCITY.
      READ 112, PCAB,TCAB,TDEW,RHOG,CPGAS,VCAB
C
      LOOP=1
      TIME = 0.0
      IPRINT1 = 1
      PI = 3.14159265359
C     WORK=METABOLIC RATE ABOVE BASAL EXCLUDING SHIVERING
      WORK=600.0
C     RMET=TOTAL METABOLIC RATE
      RMET=WORK+284.
C     ESTABLISHES SET-POINTS FOR CONTROL EQUATIONS
      TSET(1) = 98.46
      TSET(2) = 96.12
      TSET(3) = 98.64
      TSET(4) = 97.74
      TSET(5) = 94.68
      TSET(6) = 96.84
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```
      TSET(7) = 93.24
      TSET(8) = 97.56
      TSET(9) = 96.84
      TSET(10) = 97.20
      TSET(11) = 91.44
      TSET(12) = 97.56
      TSET(13) = 96.30
      TSET(14) = 98.10
C
      SWEATP = 0.0
      QSHIVP = 0.0
      STRICP = 0.0
C
C     IPRINT=NUMBER OF TIME STEPS TAKEN BETWEEN EACH PRINT-OUT
C     TIMELMT=TIME AT WHICH COMPUTATION ENDS
C     DT=TIME INCREMENT
      READ 106, IPRINT, TIMELMT, DT
C
C     IFIRST(L)=NUMBER OF FIRST ELEMENT IN THE L-TH SEGMENT
C     NO(L)=NUMBER OF ELEMENTS IN THE L-TH SEGMENT
C     L=1 DENOTES RIGHT LEG
C     L=2 DENOTES LEFT LEG
C     L=3 DENOTES RIGHT ARM
C     L=4 DENOTES LEFT ARM
      READ 107, (IFIRST(L), NO(L), L = 1, 4)
C
      IFIRST(5) = 2
      IFIRST(6) = 3
      ISUM = 3
      DO 2 L = 1, 4
    2 ISUM = ISUM+NO(L)
      PRINT 114
      PRINT 115, TIME
C
      DO 11 I = 1, ISUM
C     JB(I)=NUMBER OF RADIAL NODES IN I-TH ELEMENT
C     JH(I,K)=RADIAL NODES AT WHICH RADIAL INCREMENTS CHANGE
C     H(I,K)=K-TH RADIAL INCREMENT IN I-TH ELEMENT
      READ 108, JB(I), (JH(I, K), H(I, K), K = 1, 5)
C
C
      JBI = JB(I)
C
C     TA(I)=INITIAL TEMP OF ARTERIAL BLOOD IN I-TH ELEMENT
C     TV(I)=INITIAL TEMP OF VENOUS BLOOD IN I-TH ELEMENT
C     TE(I)=EFFECTIVE ENVIRONMENTAL FOR I-TH ELEMENT
C     TWALL(I)=TEMPERATURE OF WALLS SEEN BY I-TH ELEMENT
C     T(I,J)=INITIAL TISSUE TEMP AT J-TH NODE IN I-TH ELEMENT
      READ 109, TA(I), TV(I), TE(I), (T(I, J), J = 1, JBI)
C
      TWALL(I)=82.4
      TE(I)=82.4
C
C     JJ(I,K) DENOTE 10 NODES FOR WHICH TEMPS WILL BE PRINTED IN I-TH
C     ELEMENT
```

```
      READ 110, (JJ(I, K), K = 1, 10)
C
C     JS(I)=NODE AT WHICH EVAPORATIVE LOSS OCCURS IN I-TH ELEMENT
      RFAD 110, JS(I)
C
C     RS(I)=RADIUS OF SKIN SURFACE
      READ 109, RS(I)
C
      DO 3 K = 1, 10
      J = JJ(I, K)
 3    TP(I, K) = T(I, J)
      PRINT 117, I, (TP(I, K), K = 1, 10)
      PRINT 120, TA(I), TV(I), TE(I)
C     COMPUTE GEOMETRIC FACTORS USED TO EVALUATF COEFFICIENT IN FINITE
C     DIFFFRENCF EQUATIONS
      R = 0.0
      IF (JJ(I, 1) .EQ. 1) RAD(I, 1) = 0.0
      HP = H(I, 1)
      RP = HP
      VOLM(I, 1) = 0.0
      VOLP(I, 1) = HP*HP/4.0
      VOL(I, 1) = RP*RP
      GRADM(I, 1) = 0.0
      GRADP(I, 1) = 1.0
      K = 2
      KP = 1
      IF (JJ(I, 1) .EQ. 1) KP = 2
      DO 9 J = 2, JBI
      HM = HP
      RM = R
      R = RP
      IF (J.EQ.JS(I)) RSW(I)=R
      IF (JJ(I, KP) .EQ. J) 4,5
 4    RAD(I, KP) = R
      KP = KP+1
      IF (KP .GT. 10) KP = 1
 5    IF (K .GT. 5) 8,6
 6    IF (J-JH(I, K)) 8,7,8
 7    HP = H(I, K)
      K = K+1
 8    RP = R+HP
      VOLM(I, J) = HM*(R-HM/4.0)
      VOLP(I, J) = HP*(R+HP/4.0)
      VOL(I, J) = (RP*RP-R*R)
      GRADM(I, J) = 2.0*R/HM-1.0
 9    GRADP(I, J) = 2.0*R/HP+1.0
      VOL(I, JBI) = 0.0
      GRADP(I, JBI) = 0.0
      VOLP(I, JBI) = 0.0
      RB(I) = R
      DO 10 K = 1, 5
C
C     JP(I,K)=RADIAL NODES AT WHICH PHYSICAL PROPERTIES CHANGE VALUES IN
C     I-TH ELEMENT
C     IN THE FOLLOWING DEFINITIONS, I DENOTES THE I-TH ELEMENT AND
```

```
C     K DENOTES THE K-TH VALUE OF THE PROPERTY
C     RCT(I,K)=PRODUCT OF DENSITY AND SPECIFIC HEAT FOR TISSUE PLUS
C     BLOOD IN CAPILLARIES
C     RCA(I,K)=PRODUCT OF DENSITY AND SPECIFIC HEAT FOR BLOOD IN LARGE
C     ARTERIES
C     RCV(I,K)=PRODUCT OF DENSITY AND SPECIFIC HEAT FOR BLOOD IN LARGE
C     VEINS
C     XK(I,K)=THERMAL CONDUCTIVITY OF TISSUE
C     HMET(I,K)=METABOLIC HEAT GENERATION RATE PER UNIT VOLUME
C     QC(I,K)=PRODUCT OF VOLUMETRIC FLOW RATE, DENSITY, AND SPECIFIC
C     HEAT FOR BLOOD ENTERING CAPILLARY BEDS PER UNIT VOLUME
C     HAT(I,K)=HEAT TRANSFER COEFFICIENT FOR TRANSFER BETWEEN BLOOD IN
C     LARGE ARTERIES AND ADJACENT TISSUE
C     HVT(I,K)=CORRESPONDING QUANTITY FOR LARGE VEINS
 10   READ 111, JP(I, K), RCT(I, K), RCA(I, K), RCV(I, K), XK(I, K), HME
     1T(I, K), QC(I, K), HAT(I, K), HVT(I, K)
C
C     HTC(I)=HEAT TRANSFER COEFFICIENT AT SURFACE OF I-TH ELEMENT
C     EMIS(I)=EMISSIVITY OF I-TH ELEMENT
C     XL(I)=LENGTH OF I-TH ELEMENT
 11   READ 112, HTC(I), EMIS(I), XL(I)
C
C     QCV(K)=RELATIVE BLOOD FLOW RATE TO CAPILLARIES IN K-TH SEGMENT OF
C     CHEST
C     QCV(K)=1.0/(RO(K)**2-RI(K)**2)
      READ 112, (QCV(K), K = 1, 5)
C
      PRINT 110, (JS(I),I=1,ISUM)
      PRINT 112, (RSW(I),I=1,ISUM)
      DO 12 I = 1, ISUM
      DO 12 J = 1, 10
 12   RAD(I, J) = RAD(I, J)/RS(I)
      DO 500 I=1,ISUM
      K=1
      Z=PI*XL(I)
      VCUM(I,K)=VOL(I,1)*Z
      JBM1=JB(I)-1
      DO 502 J=2,JBM1
      IF (J.EQ.JP(I,K+1)) 501,502
  501 K=K+1
      VCUM(I,K)=0.0
  502 VCUM(I,K)=VCUM(I,K)+VOL(I,J)*Z
  500 CONTINUE
      DO 505 I=1,ISUM
      DO 505 K=1,5
C
C     F1 = FRACTION OF BLOOD FLOW OR HEAT GENERATION FROM CONTROL
C     EQUATION LV1(I,K) WHICH IS TO BE ASSIGNED TO THE K-TH REGION
C     OF I-TH ELEMENT
C     F2 AND LV2(I,K) HAVE SIMILAR MEANINGS
      READ 124, F1,F2,LV1(I,K),LV2(I,K)
C
      IF (F1.EQ.0.0) 506,507
  506 CV1(I,K)=0.0
      GO TO 508
```

```
 507 CV1(I,K)=F1/VCUM(I,K)
 508 IF (F2.EQ.0.0) 509,510
 509 CV2(I,K)=0.0
     GO TO 505
 510 CV2(I,K)=F2/VCUM(I,K)
 505 PRINT 121, F1,CV1(I,K),F2,CV2(I,K),VCUM(I,K)
C     IDENTIFY TEMPERATURES TO BE USED IN THE CONTROL EQUATIONS
 13   TS(1) = T(3, 3)
      TS(2) = T(3, 15)
      TS(3) = 0.5*(T(1, 1)+T(2, 1))
      TS(4) = 0.5*(T(1, 7)+T(2, 7))
      TS(5) = 0.5*(T(1, 15)+T(2, 15))
      TS(6) = 0.333*(T(10, 3)+T(11, 3)+T(12, 3))
      TS(7) = 0.333*(T(10, 15)+T(11, 15)+T(12, 15))
      TS(8) = T(12, 3)
      TS(9) = T(12, 15)
      TS(10) = 0.333*(T(4, 3)+T(5, 3)+T(6, 3))
      TS(11) = 0.333*(T(4, 15)+T(5, 15)+T(6, 15))
      TS(12) = T(6, 3)
      TS(13) = T(6, 15)
      TS(14) = TA(1)
C     COMPUTE SWEAT,STRIC, AND DILAT
      DO 16 I = 1, 14
      TEST = TS(I)-TSET(I)
      IF (TEST .LT. 0.0) 14,15
 14   COLD(I) = -TEST
      WARM(I) = 0.0000001
      GO TO 16
 15   WARM(I) = TEST
      COLD(I) = 0.000001
 16   CONTINUE
      WARMS = .056*WARM(2)+.276*WARM(5)+.173*WARM(7)+.043*WARM(9)+.383*W
     1ARM(11)+.069*WARM(13)
      COLDS = .056*COLD(2)+.276*COLD(5)+.173*COLD(7)+.043*COLD(9)+.383*C
     1OLD(11)+.069*COLD(13)
      WARMM = .417*WARM(4)+.19*WARM(6)+.393*WARM(10)
      COLDM = .417*COLD(4)+.19*COLD(6)+.393*COLD(10)
      SWEAT = WARM(1)*(WARMS+WARMM)*73.4814
      DILAT = SWEAT/4.
      QSHIV = COLD(1)*(COLDS+COLDM)*73.4814
      STRIC = (COLDS+COLDM)*.01961
C     IF SWEAT, STRIC, OR DILAT HAS CHANGED BY MORE THAN 5  PERCENT,
C     RECOMPUTE HEAT GENERATION AND BLOOD FLOW RATES
      Z = ABSF(SWEAT-SWEATP)/SWEAT
      ZP = ABSF(QSHIV-QSHIVP)/QSHIV
      IF (ZP .GT. Z) 17,18
 17   Z = ZP
 18   ZP = ABSF(STRIC-STRICP)/STRIC
      IF (ZP .GT. Z) 19,20
 19   Z = ZP
 20   IF (Z .GT. 0.05) 21,60
 21   SWEATP = SWEAT
      STRICP = STRIC
      QSHIVP = QSHIV
C
```

```
C     DISTRIBUTE HEAT GENERATION AND BLOOD FLOW AMONG VARIOUS SEGMENTS
C     QMET IS BASAL METABOLIC FOR ALL NODES EXCEPT MUSCLE NODES WHICH
C     ARE AFFECTED BY WORK
      QMET(1) = 49.2825
      QMET(2) = 0.3968
      QMET(3) = 179.3536
      QMET(4) = 17.0624+.417*(WORK+QSHIV)
      QMET(5) = 2.0236
      QMET(6) = 6.19+.190*(WORK+QSHIV)
      QMET(7) = 1.23
      QMET(8) = 2.3014
      QMET(9) = .3174
      QMET(10) = 18.5702+.393*(WORK+QSHIV)
      QMET(11) = 2.8172
      QMET(12) = 4.5235
      QMET(13) = .4761
      QMET(14)=0.0
C
C     BLOODFLOW (IN POUNDS/HR)
      BF(1) = 105.897
      BF(2) = 2.647+.056*DILAT
      BF(3) = 503.013
      BF(4) = 22.062+QMET(4)-STRIC
      BF(5) = 2.2062+.3*DILAT-STRIC
      BF(7) = 1.103+.2*DILAT-STRIC
      BF(8) = 1.103-STRIC
      BF(9) = 8.824+.1*DILAT-STRIC
      BF(6) = 6.618+QMET(6)+BF(9)-STRIC
      BF(13) = 6.618+.05*DILAT-STRIC
      BF(10) = 17.649+QMET(10)+BF(13)-STRIC
      BF(11) = 2.206+.294*DILAT-STRIC
      BF(12) = 2.206-STRIC
      BF(14)=0.0
      TSBF = BF(2)+BF(5)+BF(7)+BF(9)+BF(11)+BF(13)
C     CHECK FOR NEGATIVE BLOOD FLOW
      DO 22 I = 1, 13
 22   IF (BF(I) .LT. 0.) BF(I) = 0.000001
C
      DO 23 I=1,ISUM
      DO 23 K=1,5
      L1=LV1(I,K)
      L2=LV2(I,K)
      HMET(I,K)=CV1(I,K)*QMET(L1)+CV2(I,K)*QMET(L2)
   23 QC(I,K)=CV1(I,K)*BF(L1)+CV2(I,K)*BF(L2)
C
C     COMPUTE EVAPORATIVE FLUX AT SURFACE OF I-TH ELEMENT, EV(I)
      EV(1)=0.09300*SWEAT
      EV(2)=0.09300*SWEAT
      EV(3)= 0.063787*SWEAT
      EV(4)= 0.022821*SWEAT
      EV(5)= 0.022821*SWEAT
      EV(6)= 0.033389*SWEAT
      EV(7)= 0.022821*SWEAT
      EV(8)= 0.022821*SWEAT
      EV(9)= 0.033389*SWEAT
```

```
      EV(10)= 0.024555*SWEAT
      EV(11)= 0.024555*SWEAT
      EV(12)= 0.040650*SWEAT
      EV(13)= 0.024555*SWEAT
      EV(14)= 0.024555*SWEAT
      EV(15)= 0.040650*SWEAT
C
C     CEVAP=COEFFICIENT IN EXPRESSION FOR MAXIMUM EVAPORATION RATE
      CEVAP=0.126*SQRT(VCAB/PCAB)*(TCAB+460.0)**1.04
      SWET=0.0
      DO 406 I=1,ISUM
      JZ=JS(I)
      TSUR=T(I,JZ)
      Z=VPP(TSUR)-VPP(TDEW)
C     INSENSIBLE EVAPORATION RATE=6.66*Z
      SWET=SWET+2.0*PI*RSW(I)*XL(I)*EV(I)
      EV(I)=EV(I)+6.66*Z
      EMX=CEVAP*Z
C     EMX=MAXIMUM EVAPORATIVE FLUX
      IF (EV(I).GT.EMX) EV(I)=EMX
C     COMPUTE HEAT TRANSFER COEFFICIENT FOR RADIATION
      JZ=JB(I)
      TSZ=T(I,JZ)+460.0
      TWZ=TWALL(I)+460.0
      HRAD(I)=0.1713E-8*EMIS(I)*(TSZ**3+TSZ*TSZ*TWZ+TSZ*TWZ*TWZ+TWZ**3)
  406 CONTINUE
  405 DO 31 I=1,ISUM
      JBM1 = JB(I)-1
      K = 1
      QCP = QC(I, K)
      VQC(I) = 0.0
      DO 31 J = 1, JBM1
      QCM = QCP
      IF (K .GT. 5) 31,29
 29   IF (J-JP(I, K)) 31,30,31
 30   QCP = QC(I, K)
      K = K+1
 31   VQC(I) = VQC(I)+VOL(I, J)*QCP
      CARDIAC=0.0
      DO 401 I=1,ISUM
  401 CARDIAC=CARDIAC+VQC(I)*PI*XL(I)
      BFNASA=0.0
      DO 402 I=1,13
  402 BFNASA=BFNASA+BF(I)
      PRINT 121, CARDIAC,BFNASA,SWET,SWEAT
  403 DO 32 L=1,4
C     COMPUTE BLOOD FLOW RATE TO LUNGS
      N = NO(L)
      I = IFIRST(L)+N-1
      VQ(I) = 0.0
      AQ(I) = VQC(I)
      DO 32 INVRS = 2, N
      I = I-1
      VQ(I) = AQ(I+1)*XL(I+1)/XL(I)
 32   AQ(I) = VQ(I)+VQC(I)
```

```
      VQ(3) = 0.0
      AQ(3) = VQC(3)
      I1 = IFIRST(1)
      I2 = IFIRST(2)
      VQ(2) = (XL(I1)*AQ(I1)+XL(I2)*AQ(I2))/XL(2)
      AQ(2) = VQ(2)+VQC(2)
      Z = 0.0
      DO 33 L = 3, 6
      LI = IFIRST(L)
   33 Z = Z+XL(LI)*AQ(LI)
      QVL = Z/XL(1)+VQC(1)
C
      DO 34 L = 3, 6
      LI = IFIRST(L)
   34 P(L) = XL(LI)*AQ(LI)/Z
      DO 56 I = 1, ISUM
      AS(I)=RSW(I)
      A1(I) = RB(I)
      JBI = JB(I)
      K = 1
      RCTP = RCT(I, K)
      RCAP = RCA(I, K)
      RCVP = RCV(I, K)
      XKP = XK(I, K)
      HMETP = HMET(I, K)
      QCP = QC(I, K)
      IF (I-1) 35,35,36
C     DISTRIBUTE BLOOD FLOW TO LUNGS
   35 QCVP = QVL*QCV(K)
      GO TO 37
   36 QCVP = 0.0
   37 HATP = HAT(I, K)
      HVTP = HVT(I, K)
      K = 2
      AERC(I) = 0.0
      VERC(I) = 0.0
      AEH2(I) = 0.0
      VEH3(I) = 0.0
      AR(I, 1) = 0.0
      VQC(I) = 0.0
      DO 44 J = 1, JBI
      RCTM = RCTP
      RCAM = RCAP
      RCVM = RCVP
      XKM = XKP
      HMETM = HMETP
      QCM = QCP
      QCVM = QCVP
      HATM = HATP
      HVTM = HVTP
      IF (K .GT. 5) 43,38
   38 IF (J-JP(I, K)) 43,39,43
   39 RCTP = RCT(I, K)
      RCAP = RCA(I, K)
      RCVP = RCV(I, K)
```

```
      XKP = XK(I, K)
      HMETP = HMET(I, K)
      QCP = QC(I, K)
      IF (I-1) 40,40,41
40    QCVP = QVL*QCV(K)
      GO TO 42
41    QCVP = 0.0
42    HATP = HAT(I, K)
      HVTP = HVT(I, K)
      K = K+1
43    EPRC = VOLM(I, J)*RCTM+VOLP(I, J)*RCTP
      AR(I, J) = -GRADM(I, J)*XKM*DT/(2.0*EPRC)
      BR(I, J) = (GRADM(I, J)*XKM+GRADP(I, J)*XKP+VOLM(I, J)*(QCM+HATM+Q
     1CVM+HVTM)+VOLP(I, J)*(QCP+HATP+QCVP+HVTP))*DT/(2.0*EPRC)
      CR(I, J) = -GRADP(I, J)*XKP*DT/(2.0*EPRC)
      DHMET(I, J) = (VOLM(I, J)*HMETM+VOLP(I, J)*HMETP)*DT/EPRC
      AERC(I) = AERC(I)+VOL(I, J)*RCAP
      VERC(I) = VERC(I)+VOL(I, J)*RCVP
      VQC(I) = VQC(I)+VOL(I, J)*QCP
      AEH2(I) = AEH2(I)+VOL(I, J)*HATP
      VEH3(I) = VEH3(I)+VOL(I, J)*HVTP
      DA(I, J) = (VOLM(I, J)*(QCM+HATM)+VOLP(I, J)*(QCP+HATP))*DT/(-2.0*
     1EPRC)
      DV(I, J) = (VOLM(I, J)*(QCVM+HVTM)+VOLP(I, J)*(QCVP+HVTP))*DT/(-2.
     10*EPRC)
      WA(I, J) = -(VOLM(I, J)*(QCVM+HATM)+VOLP(I, J)*(QCVP+HATP))/2.0
      WV(I, J) = -(VOLM(I, J)*(QCM+HVTM)+VOLP(I, J)*(QCP+HVTP))/2.0
      IF (J.EQ.JS(I)) AS(I)=AS(I)*DT/EPRC
44    CONTINUE
      AQ(I) = AQ(I)/2.0
      VQ(I) = VQ(I)/2.0
      VQC(I) = VQC(I)/2.0
      AEH2(I) = AEH2(I)/2.0
      VEH3(I) = VEH3(I)/2.0
      IF (I-1) 45,45,46
45    QVL = QVL/2.0
      DAA(I) = AERC(I)/DT+QVL+AEH2(I)
      DAV(I) = 0.0
      DAAP(I) = 0.0
      DVA(I) = 0.0
      DVV(I) = VERC(I)/DT+QVL+VEH3(I)
      DVVP(I) = QVL-VQC(I)
      GO TO 47
46    DAA(I) = AERC(I)/DT+AQ(I)+AEH2(I)
      DAV(I) = 0.0
      DAAP(I) = AQ(I)
      DVA(I) = 0.0
      DVV(I) = VERC(I)/DT+VQ(I)+VQC(I)+VEH3(I)
      DVVP(I) = VQ(I)
47    CONTINUE
      A1(I) = A1(I)*DT/EPRC
      A(I) = A1(I)*HTC(I)
      ARAD(I)=A1(I)*HRAD(I)
      BR(I, JBI) = BR(I, JBI)+A(I)+ARAD(I)
      DO 48 J = 1, JBI
```

```
      WAT(I, J) = WA(I, J)
48    WVT(I, J) = WV(I, J)
      DO 55 J = 1, JBI
      IF (J-1) 49,49,50
49    SMLAR(I, 1) = 1.0/(1.0+BR(I, 1))
      GO TO 51
50    SMLAR(I, J) = 1.0/(1.0+BR(I, J)-AR(I, J)*SMLBR(I, J-1))
51    SMLBR(I, J) = SMLAR(I, J)*CR(I, J)
      SMLCR(I, J) = SMLAR(I, J)*AR(I, J)
      IF (J-1) 52,52,53
52    DA(I, 1) = SMLAR(I, 1)*DA(I, 1)
      DV(I, 1) = SMLAR(I, 1)*DV(I, 1)
      GO TO 54
53    DA(I, J) = SMLAR(I, J)*DA(I, J)-SMLCR(I, J)*DA(I, J-1)
      DV(I, J) = SMLAR(I, J)*DV(I, J)-SMLCR(I, J)*DV(I, J-1)
      IF (J.EQ.JBI) GO TO 25
54    WA(I, J+1) = WA(I, J+1)-SMLBR(I, J)*WA(I, J)
      WV(I, J+1) = WV(I, J+1)-SMLBR(I, J)*WV(I, J)
   25 DAA(I) = DAA(I)-WA(I, J)*DA(I, J)
      DAV(I) = DAV(I)-WA(I, J)*DV(I, J)
      DVA(I) = DVA(I)-WV(I, J)*DA(I, J)
55    DVV(I) = DVV(I)-WV(I, J)*DV(I, J)
56    SMLBR(I, JBI) = 0.0
      DO 58 L = 1, 4
      N = NO(L)
      DO 58 INVRS = 1, N
      II = N+1-INVRS
      I = IFIRST(L)+II-1
      DAV(I) = -DAV(I)/DAA(I)
      DAAP(I) = DAAP(I)/DAA(I)
      DVV(I) = DVV(I)+DVA(I)*DAV(I)
      SZ(II, L) = -DVA(I)*DAAP(I)/DVV(I)
      IF (II-1) 58,58,57
57    DVA(I-1) = DVA(I-1)-DVVP(I-1)*SZ(II, L)
58    CONTINUE
      DAV(1) = -DAV(1)/DAA(1)
      I1 = IFIRST(1)
      I2 = IFIRST(2)
      P(1) = VQ(I1)+VQC(I1)
      P(2) = VQ(I2)+VQC(I2)
      Z = P(1)+P(2)
      P(1) = P(1)/Z
      P(2) = P(2)/Z
      DAV(2) = -DAV(2)/DAA(2)
      DAAP(2) = DAAP(2)/DAA(2)
      DVA(2) = DVA(2)-DVVP(2)*(P(2)*SZ(1, 2)+P(1)*SZ(1, 1))
      DVV(2) = DVV(2)+DVA(2)*DAV(2)
      SZ(1, 5) = -DVA(2)*DAAP(2)/DVV(2)
      DAV(3) = -DAV(3)/DAA(3)
      DAAP(3) = DAAP(3)/DAA(3)
      DVV(3) = DVV(3)+DVA(3)*DAV(3)
      SZ(1, 6) = -DVA(3)*DAAP(3)/DVV(3)
      Z = 0.0
      DO 59 L = 3, 6
59    Z = Z+P(L)*SZ(1, L)
```

```
      DVA(1) = DVA(1)-DVVP(1)*Z
      DVV(1) = DVV(1)+DVA(1)*DAV(1)
C     COMPUTE RATE OF HEAT LOSS THROUGH RESPIRATORY TRACT
   60 TRES=0.25*(TA(3)+TV(3))+0.5*TV(1)
C     QLR=EVAPORATIVE RATE OF LOSS
      QLR=1040.0*0.0418*RHOG*RMET*(VPP(TRES)-0.8*VPP(TDEW))*18.0/
     1(29.0*PCAB)
C     QSR=SENSIBLE RATE OF LOSS
      QSR=0.0418*RHOG*RMET*CPGAS*(TRES-TCAB)
      QR=QLR+QSR
      DO 61 I = 1, ISUM
   61 TE(I) = TE(I)+TSTEP
      TER = TER+TSTEP
      DO 81 I = 1, ISUM
      AEHT(I) = 0.0
      VEHT(I) = 0.0
      JBI = JB(I)
      DO 62 J = 1, JBI
      AEHT(I) = AEHT(I)-WAT(I, J)*T(I, J)
   62 VEHT(I) = VEHT(I)-WVT(I, J)*T(I, J)
      IF (I-2) 68,70,63
   63 IF (I-3) 70,74,64
   64 IF (I-IFIRST(1)) 73,72,65
   65 IF (I-IFIRST(2)) 73,72,66
   66 IF (I-IFIRST(3)) 73,74,67
   67 IF (I-IFIRST(4)) 73,74,73
   68 TAIN = TA(1)
      TVIN = -P(6)*0.25*QR/(2.0*PI*AQ(3)*XL(3))
      DO 69 L = 3, 6
      LI = IFIRST(L)
   69 TVIN = TVIN+P(L)*TV(LI)
      GO TO 75
   70 TAIN = TA(1)
      TVIN = 0.0
      DO 71 L = 1, 2
      LI = IFIRST(L)
   71 TVIN = TVIN+P(L)*TV(LI)
      GO TO 76
   72 TAIN = TA(2)
      TVIN = TV(I+1)
      GO TO 76
   73 TAIN = TA(I-1)
      TVIN = TV(I+1)
      GO TO 76
   74 TAIN = TA(1)
      TVIN = TV(I+1)
      GO TO 76
   75 DAC(I) = (AERC(I)/DT-QVL-AEH2(I))*TA(I)+AEHT(I)
      DVC(I) = (VERC(I)/DT-QVL-VEH3(I))*TV(I)+DVVP(I)*TVIN+VEHT(I)
      GO TO 77
   76 DAC(I) = (AERC(I)/DT-AQ(I)-AEH2(I))*TA(I)+AQ(I)*TAIN+AEHT(I)
      DVC(I) = (VERC(I)/DT-VQ(I)-VQC(I)-VEH3(I))*TV(I)+VQ(I)*TVIN+VEHT(I
     1)
   77 DO 80 J = 1, JBI
      D = DHMET(I, J)-AR(I, J)*T(I, J-1)+(1.0-BR(I, J))*T(I, J)-CR(I, J)
```

```
     1*T(I, J+1)
      IF (J.EQ.JS(I)) D=D-2.0*AS(I)*EV(I)
      IF (J-JBI) 79,78,79
 78   D = D+2.0*A(I)*TE(I)+2.0*ARAD(I)*TWALL(I)
 79   Q(J) = SMLAR(I, J)*D-SMLCR(I, J)*Q(J-1)
      DAC(I) = DAC(I)-WA(I, J)*(Q(J)-DA(I, J)*TA(I)-DV(I, J)*TV(I))
 80   DVC(I) = DVC(I)-WV(I, J)*(Q(J)-DA(I, J)*TA(I)-DV(I, J)*TV(I))
      DAC(I) = DAC(I)/DAA(I)
      DO 81 J = 1, JBI
 81   T(I, J) = Q(J)-DA(I, J)*TA(I)-DV(I, J)*TV(I)
      DVC(1) = DVC(1)-0.5*QR/(PI*XL(1))
      DAC(3) = DAC(3)-0.25*QR/(DAA(3)*PI*XL(3))
      DO 83 L = 1, 4
      N = NO(L)
      DO 83 INVRS = 1, N
      II = N+1-INVRS
      I = IFIRST(L)+II-1
      GZ(II, L) = (DVC(I)-DVA(I)*DAC(I))/DVV(I)
      IF (II-1) 83,83,82
 82   DVC(I-1) = DVC(I-1)+DVVP(I-1)*GZ(II, L)
 83   CONTINUE
      DVC(2) = DVC(2)+DVVP(2)*(P(1)*GZ(1, 1)+P(2)*GZ(1, 2))
      GZ(1, 5) = (DVC(2)-DVA(2)*DAC(2))/DVV(2)
      GZ(1, 6) = (DVC(3)-DVA(3)*DAC(3))/DVV(3)
      I = 1
      Z = P(6)*(GZ(1, 6)-0.25*QR/(2.0*PI*AQ(3)*XL(3)))
      DO 84 L = 3, 5
 84   Z = Z+P(L)*GZ(1, L)
      TV(1) = (DVC(1)-DVA(1)*DAC(1)+DVVP(1)*Z)/DVV(1)
      TA(1) = DAC(1)+DAV(1)*TV(1)
      DO 85 I = 2, 3
      L = I+3
      TV(I) = GZ(1, L)+SZ(1, L)*TA(1)
 85   TA(I) = DAC(I)+DAV(I)*TV(I)+DAAP(I)*TA(1)
      DO 89 L = 1, 4
      IF (L-2) 86,86,87
 86   TAIN = TA(2)
      GO TO 88
 87   TAIN = TA(1)
 88   N = NO(L)
      I = IFIRST(L)
      TV(I) = GZ(1, L)+SZ(1, L)*TAIN
      TA(I) = DAC(I)+DAV(I)*TV(I)+DAAP(I)*TAIN
      DO 89 II = 2, N
      I = IFIRST(L)+II-1
      TV(I) = GZ(II, L)+SZ(II, L)*TA(I-1)
 89   TA(I) = DAC(I)+DAV(I)*TV(I)+DAAP(I)*TA(I-1)
      DO 91 I = 1, ISUM
      JBI = JB(I)
      DO 90 INVRS = 1, JBI
      J = JB(I)-INVRS+1
 90   T(I, J) = T(I, J)-SMLBR(I, J)*T(I, J+1)-DA(I, J)*TA(I)-DV(I, J)*TV
     1(I)
 91   CONTINUE
      TIME = TIME+DT
```

```
      IF (IPRINT1-IPRINT) 92,93,93
 92   IPRINT1 = IPRINT1+1
      GO TO 13
 93   IPRINT1 = 1
      PRINT 114
      PRINT 116, TIME
      DO 95 I = 1, ISUM
      DO 94 K = 1, 10
      J = JJ(I, K)
 94   TP(I, K) = T(I, J)
      PRINT 118, I, (RAD(I, K), K = 1, 10)
      PRINT 119, (TP(I, K), K = 1, 10)
      PRINT 120, TA(I), TV(I), TE(I)
 95   CONTINUE
      GWISS=0.0
      DO 410 I=1,ISUM
      JBM1=JB(I)-1
      Z=PI*XL(I)
      K=1
      DO 410 J=1,JBM1
      IF (K.GT.5) GO TO 410
      IF (J.EQ.JP(I,K)) 412,410
  412 HWP=HMET(I,K)
      K=K+1
  410 GWISS=GWISS+Z*HWP*VOL(I,J)
      RMAT=0.0
      DO 24 I=1,13
   24 RMAT=RMAT+QMET(I)
      PRINT 121, GWISS,RMAT
      IF (TIME-TIMELMT) 13,97,97
 97   CONTINUE
      PUNCH 103
      IF (LOOP.EQ.2)  GO TO 399
      TIME=0.0
      DO 400 I=1,ISUM
      TWALL(I)=50.0
  400 TE(I)=50.0
      IPRINT=80
      LOOP=2
      GO TO 13
C     CONVERT RESULTS TO RADIAL POSITION IN CM AND TEMPERATURE IN CENT.
  399 DO 98 I=1,ISUM
      TA(I)=(TA(I)-32.0)/1.8
      TV(I)=(TV(I)-32.0)/1.8
      TE(I)=(TE(I)-32.0)/1.8
      DO 98 K=1,10
      RAD(I,K)=RAD(I,K)*RS(I)*30.48
   98 TP(I,K)=(TP(I,K)-32.0)/1.8
      DO 125 I=1,ISUM
      PRINT 118, I, (RAD(I, K), K = 1, 10)
      PRINT 119, (TP(I, K), K = 1, 10)
  125 PRINT 120, TA(I), TV(I), TE(I)
C
 102  FORMAT  (50H   E. H. WISSLER   MULTI-ELEMENT MAN   CH041073
     1)
```

```
103  FORMAT  (80H
    1                                                            )
104  FORMAT  (23H I= 1 DENOTES THE CHEST,/
    1 25H I= 2 DENOTES THE ABDOMEN,/
    2 22H I= 3 DENOTES THE HEAD,/
    3 51H I= 4 DENOTES THE PROXIMAL SEGMENT OF THE RIGHT LEG,/
    4 49H I= 5 DENOTES THE MEDIAL SEGMENT OF THE RIGHT LEG,/
    5 49H I= 6 DENOTES THE DISTAL SEGMENT OF THE RIGHT LEG,/
    6 50H I= 7 DENOTES THE PROXIMAL SEGMENT OF THE LEFT LEG,/
    7 48H I= 8 DENOTES THE MEDIAL SEGMENT OF THE LEFT LEG,/
    8 48H I= 9 DENOTES THE DISTAL SEGMENT OF THE LEFT LEG)
105  FORMAT  (51H I=10 DENOTES THE PROXIMAL SEGMENT OF THE RIGHT ARM,/
    1 49H I=11 DENOTES THE MEDIAL SEGMENT OF THE RIGHT ARM,/
    2 49H I=12 DENOTES THE DISTAL SEGMENT OF THE RIGHT ARM,/
    3 50H I=13 DENOTES THE PROXIMAL SEGMENT OF THE LEFT ARM,/
    4 48H I=14 DENOTES THE MEDIAL SEGMENT OF THE LEFT ARM,/
    5 48H I=15 DENOTES THE DISTAL SEGMENT OF THE LEFT ARM)
106  FORMAT  (I12,4F12.6)
107  FORMAT  (10I5)
108  FORMAT  (I12/(I12,F12.8,I12,F12.8,I12,F12.8))
109  FORMAT  (3F12.8/(6F12.8))
110  FORMAT  (10I5)
111  FORMAT  (I12,5F12.8/(6F12.8))
112  FORMAT  (6F12.8)
113  FORMAT  (2I12,F12.8)
114  FORMAT  (1H1)
115  FORMAT  (6H TIME=F6.4,105H       R/A=0.0      0.2        0.3        0.
    14         0.5         0.6         0.7         0.8         0.9        1.0
    2  /)
116  FORMAT  (6H TIME=F6.1/)
117  FORMAT  (6H     I=I2,F19.5,9F10.5)
118  FORMAT  (6H     I=I2,9H  R/A=    ,10F10.5)
119  FORMAT  (17X,10F10.5)
120  FORMAT  (8X, 10H    TA(I)=,F9.5, 11H     TV(I)=,F9.5, 11H     TE(I
    1)=,F9.5)
121  FORMAT  (6X,6E20.5)
122  FORMAT  (I5)
123  FORMAT  (4E20.10)
 124 FORMAT (2F10.8,2I10)
     END
     FUNCTION VPP(ZTE)
     DIMENSION JH(15,5), JB(15), H(15,5), VOLM(15,21), VOLP(15,21), VOL
    1(15,21), GRADM(15,21), GRADP(15,21), W1M(15,21), W2M(15,21), W3M(1
    25,21), W1P(15,21), W2P(15,21), W3P(15,21), JJ(15,10)
     DIMENSION IFIRST(6), NO(6), GZ(5,6), SZ(5,6), CRP(15)
     DIMENSION TA(15), TV(15), T(15,21), TE(15), TP(15,20)
     DIMENSION JP(15,5), RCT(15,5), RCA(15,5), RCV(15,5), XK(15,5), HME
    1T(15,5), QC(15,5), QCV(5), XL(15), HAT(15,5), HVT(15,5), WA(15,21)
    2, WV(15,21), AERC(15), VERC(15), AQ(15), VQ(15), VQC(15), AEH2(15)
    3, VEH3(15), AR(15,21), BR(15,21), CR(15,21), DHMET(15,21), DA(15,2
    41), DV(15,21), A1(15), A(15), AJBM1(15), AJBM2(15), SMLAR(15,21),
    5SMLBR(15,21), SMLCR(15,21), AEHT(15), VEHT(15), Q(21), AEHTP(15),
    6VEHTP(15), HTC(15), DPDT(15), XLAT(15), XMK(15), FW(15), XMD(15)
     DIMENSION WAE(15), WVE(15), DAA(15), DAV(15), DVA(15), DVV(15), DA
    1C(15), DVC(15), DAAP(15), DVVP(15), WAT(15,21), WVT(15,21), P(6)
```

```
 DIMENSION QMET(15), BF(15), RB(15)
 DIMENSION TS(15), TSET(15), WARM(15), COLD(15), QSWEAT(15), EV(15)
 DIMENSION RAD(15,10), RS(15), JS(15)
 DIMENSION RSW(15),AS(15)
 COMMON JH, JB, H, VOLM, VOLP, VOL, GRADM, GRADP, W1M, W2M, W3M, W1
1P, W2P, W3P, JJ, IFIRST, NO, GZ, SZ, TA, TV, T, TE, JP, RCT, RCA,
2RCV, XK, HMET, CRP, QC, QCV, HAT, HVT, WA, WV, AERC, VERC, AQ, VQ,
3 VQC, AEH2, VEH3, AR, BR, CR, XL, DHMET, DA, DV, A1, A, AJBM1, AJB
4M2, SMLAR, SMLBR, SMLCR, AEHT, VEHT, HTC, DPDT, XLAT, XMK, FW, XMD
5, WAE, WVE, DAA, DAV, DVA, DVV, DAC, DVC, DAAP, DVVP, WAT, WVT, P
 TTE=ZTE+460.0
 VPP=0.178*EXP(9583.0*(0.0019608-1.0/TTE))
 RETURN
 END
 END
```

```
C      DATA FOR PROGRAM MEM.
C
 JUNE 25, 1969.  TRANSIENT STATE COOLING.  WORK = 600.  RADIATION INCLUDED.
 14.7           70.0            55.0           0.0761          0.238         40.0
          160    2.0            .00125         1.60            75.0
   4      3      7      3    10      3    13      3
          15
           1   0.08576                  5    0.057                      6    0.00425
           9   0.002125                22
96.52132121 96.49187175 75.00000000
96.50998195 96.51772920 96.52251197 96.52254639 96.52129607 95.18628905
94.83664706 94.44772185 94.01323842 93.77626490 93.52519919 93.26658171
93.00787667 92.74897960 92.48978636
   1     3     5     7     9    11    12    13    14    15
  15
  0.42554
           1 29.261        16.648         8.324          0.242

           2 51.79          0.0           0.0            0.242

           5 51.79          0.0           0.0            0.242

          11 40.0           0.0           0.0            0.121

          22

 1.689        0.95          1.207
          20
           1   0.08576                  5    0.057                      6    0.00425
           9   0.002125                15    0.00045
96.52131478 96.67636611 75.00000000
96.89774880 96.89875572 96.89863151 96.88946221 96.78647338 95.42476605
95.10003786 94.74002826 94.33891292 94.12049058 93.88929187 93.41319075
92.93675553 92.45961096 91.98138432 91.79688617 91.61274984 91.42856918
91.24479519 91.06108048
   1     5     9    12    14    15    16    17    18    20
  20
  0.42554
           1 41.8           2.773         2.773          0.242

           2 51.79          0.0           0.0            0.242

           5 51.79          0.0           0.0            0.242

          11 47.10          0.0           0.0            0.121

          15   1.6          0.0           0.0            0.0665

 1.689        0.95          1.207
          15
           1   0.03520                  6    0.01635                    9    0.004075
          22                           22
96.25440405 95.26184610 75.00000000
96.41889193 96.41340826 96.37851233 96.30037026 96.11383651 95.66849281
95.20525114 94.48465090 93.35029859 92.96335897 92.53002824 91.61859551
```

```
90.72229242 89.84058826 88.97300085
   1     3     5     7     9    11    12    13    14    15
  15
  0.2495
           1 10.358       22.964       22.964       0.242

           2 47.486        2.386        2.386       0.242

           3 51.79         0.0         0.0          0.242

          11 47.06         0.0         0.0          0.121

          22

 1.829       0.95        1.0
          15
           1  0.04074              6  0.0156                  9  0.0078
          22                      22
96.52130783 96.71589723 75.00000000
97.42802847 97.42787084 97.42707763 97.42418004 97.41389152 97.37627567
97.33367996 97.26248203 97.14071454 97.04694991 96.92437011 96.72811610
96.37962999 95.80123180 94.86245905
   1     3     5     7     9    11    12    13    14    15
  15
  0.2973
           1 36.253        8.612        8.612       0.242

           2 51.79         0.0         0.0          0.242

          11 43.0          0.0         0.0          0.121

          22

          22

 1.917       0.95        0.587
          15
           1  0.02094              6  0.0156                  9  0.0078
          22                      22
96.52129218 96.60487486 75.00000000
97.41947805 97.41915891 97.41641512 97.40900252 97.39362812 97.36273531
97.31918326 97.24555125 97.12050145 97.02505281 96.90103894 96.70232528
96.34988444 95.76767257 94.82790779
   1     3     5     7     9    11    12    13    14    15
  15
  0.1983
           1 12.378       21.8445      21.8445      0.242

           2 51.79         0.0         0.0          0.242

          11 43.0          0.0         0.0          0.121

          22

          22
```

```
1.917       0.95        1.174
        15
         1  0.0102                  9  0.0078              22
        22                         22
96.52127636 96.43677464 75.00000000
97.35008446 97.34951371 97.34436844 97.33183031 97.31073630 97.27893131
97.23286090 97.16729466 97.07482747 96.97884743 96.85464646 96.65352576
96.29575305 95.70825352 94.76749265
  1    3    5    7    9    11   12   13   14   15
 15
 0.1284
         1 10.358       22.964      22.964      0.242

         2 47.336        2.469       2.469      0.242

         3 51.79         0.0         0.0        0.242

        11 43.0          0.0         0.0        0.121

        22

1.917       0.95        1.174
        15
         1  0.04074                 6  0.0156              9  0.0078
        22                         22
96.52130783 96.71589723 75.00000000
97.42802847 97.42787084 97.42707763 97.42418004 97.41389152 97.37627567
97.33367996 97.26248203 97.14071454 97.04694991 96.92437011 96.72811610
96.37962999 95.80123180 94.86245905
  1    3    5    7    9    11   12   13   14   15
 15
 0.2973
         1 36.253        8.612       8.612      0.242

         2 51.79         0.0         0.0        0.242

        11 43.0          0.0         0.0        0.121

        22

        22

1.917       0.95        0.587
        15
         1  0.02094                 6  0.0156              9  0.0078
        22                         22
96.52129218 96.60487486 75.00000000
97.41947805 97.41915891 97.41641512 97.40900252 97.39362812 97.36273531
97.31918326 97.24555125 97.12050145 97.02505281 96.90103894 96.70232528
96.34988444 95.76767257 94.82790779
  1    3    5    7    9    11   12   13   14   15
 15
 0.1983
         1 12.378       21.8445     21.8445     0.242
```

```
         2 51.79          0.0          0.0           0.242

        11 43.0           0.0          0.0           0.121

        22

        22

 1.917       0.95        1.174
        15
         1  0.0102                 9  0.0078               22
        22                        22
96.52127636 96.43677464 75.00000000
97.35008446 97.34951371 97.34436844 97.33183031 97.31073630 97.27893131
97.23286090 97.16729466 97.07482747 96.97884743 96.85464646 96.65352576
96.29575305 95.70825352 94.76749265
   1    3    5    7    9   11   12   13   14   15
  15
  0.1284
         1 10.358         22.964       22.964        0.242

         2 47.336          2.469        2.469        0.242

         3 51.79           0.0          0.0          0.242

        11 43.0            0.0          0.0          0.121

        22

 1.917       0.95        1.174
        15
         1  0.02584                6  0.00630                9  0.00315
        22                        22
96.52131152 96.50064769 75.00000000
97.37118370 97.36976180 97.36084748 97.33433755 97.26719062 97.09807930
97.01684564 96.91590997 96.78957906 96.71406601 96.62921108 96.39467305
96.01788861 95.44439904 94.59083344
   1    3    5    7    9   11   12   13   14   15
  15
  0.167
         1 19.8           17.7         17.7          0.242

         2 51.79           0.0          0.0          0.242

        11 43.0            0.0          0.0          0.121

        22

        22

 2.072       0.95        0.489
        15
         1  0.02184                6  0.00630                9  0.00315
        22                        22
```

```
96.52129352 96.46243291 75.00000000
97.35963863 97.35755160 97.34565017 97.31368239 97.24218326 97.08533131
97.00471244 96.90431057 96.77856035 96.70340455 96.61897659 96.38491177
96.00800785 95.43422913 94.58073987
  1    3    5    7    9   11   12   13   14   15
 15
 0.147
          1 21.82        16.56        16.56        0.242

          2 51.79         0.0          0.0         0.242

         11 43.0          0.0          0.0         0.121

         22

         22

 2.072        0.95         0.978
         15
          1  0.01264                 6  0.00632              9  0.00316
         22                         22
96.52127687 96.34486404 75.00000000
97.31687437 97.30086938 97.26605311 97.22025343 97.14996225 97.03976202
96.96094792 96.86248482 96.73915928 96.66553955 96.58293659 96.35096616
95.97355294 95.39793703 94.54264523
  1    3    5    7    9   11   12   13   14   15
 15
 0.10112
          1 21.82        16.56        16.56        0.242

          2 51.79         0.0          0.0         0.242

         11 43.0          0.0          0.0         0.121

         22

         22

 2.072        0.95         0.978
         15
          1  0.02584                 6  0.00630              9  0.00315
         22                         22
96.52131152 96.50064769 75.00000000
97.37118370 97.36976180 97.36084748 97.33433755 97.26719062 97.09807930
97.01684564 96.91590997 96.78957906 96.71406601 96.62921108 96.39467305
96.01788861 95.44439904 94.59083344
  1    3    5    7    9   11   12   13   14   15
 15
 0.167
          1 19.8         17.7         17.7         0.242

          2 51.79         0.0          0.0         0.242

         11 43.0          0.0          0.0         0.121
```

```
          22

          22

 2.072      0.95       0.489
          15
           1  0.02184             6  0.00630              9  0.00315
          22                     22
96.52129352 96.46243291 75.00000000
97.35963863 97.35755160 97.34565017 97.31368239 97.24218326 97.08533131
97.00471244 96.90431057 96.77856035 96.70340455 96.61897659 96.38491177
96.00800785 95.43422913 94.58073987
  1    3    5    7    9   11   12   13   14   15
 15
 0.147
           1 21.82       16.56       16.56       0.242

           2 51.79        0.0         0.0        0.242

          11 43.0         0.0         0.0        0.121

          22

          22

 2.072      0.95       0.978
          15
           1  0.01264             6  0.00632              9  0.00316
          22                     22
96.52127687 96.34486404 75.00000000
97.31687437 97.30086938 97.26605311 97.22025343 97.14996225 97.03976202
96.96094792 96.86248482 96.73915928 96.66553955 96.58293659 96.35096616
95.97355294 95.39793703 94.54264523
  1    3    5    7    9   11   12   13   14   15
 15
 0.10112
           1 21.82       16.56       16.56       0.242

           2 51.79        0.0         0.0        0.242

          11 43.0         0.0         0.0        0.121

          22

          22

 2.072      0.95       0.978
 8.49787    8.49787    0.0         0.0         0.0
0.01171   0.0              3        14
0.31828   0.0              3        14
0.5       0.0              4        14
0.5       0.0              5        14
0.0       0.0             14        14
0.03375   0.0              3        14
0.63626   0.0              3        14
```

0.5	0.0	4	14
0.5	0.0	5	14
0.0	0.0	14	14
0.00477	0.0	1	14
0.06435	0.0	1	14
0.93088	0.0	1	14
1.0	0.0	2	14
0.0	0.0	14	14
0.00369	0.0	10	14
0.21727	0.0	10	14
0.22096	0.0	11	14
0.0	0.0	14	14
0.0	0.0	14	14
0.00074	0.0	10	14
0.19585	0.0	10	14
0.19659	0.0	11	14
0.0	0.0	14	14
0.0	0.0	14	14
0.00019	0.00116	10	12
0.00241	0.01462	10	12
0.07985	0.48422	10	12
0.08245	0.5	11	13
0.0	0.0	14	14
0.00369	0.0	10	14
0.21727	0.0	10	14
0.22096	0.0	11	14
0.0	0.0	14	14
0.0	0.0	14	14
0.00074	0.0	10	14
0.19585	0.0	10	14
0.19659	0.0	11	14
0.0	0.0	14	14
0.0	0.0	14	14
0.00019	0.00116	10	12
0.00241	0.01462	10	12
0.07985	0.48422	10	12
0.08245	0.5	11	13
0.0	0.0	14	14
0.00161	0.0	6	14
0.15072	0.0	6	14
0.15233	0.0	7	14
0.0	0.0	14	14
0.0	0.0	14	14
0.00272	0.0	6	14
0.23326	0.0	6	14
0.23598	0.0	7	14
0.0	0.0	14	14
0.0	0.0	14	14
0.00099	0.00444	6	8
0.11070	0.49556	6	8
0.11169	0.5	7	9
0.0	0.0	14	14
0.0	0.0	14	14
0.00161	0.0	6	14
0.15072	0.0	6	14

0.15233	0.0	7	14
0.0	0.0	14	14
0.0	0.0	14	14
0.00272	0.0	6	14
0.23326	0.0	6	14
0.23598	0.0	7	14
0.0	0.0	14	14
0.0	0.0	14	14
0.00099	0.00444	6	8
0.11070	0.49556	6	8
0.11169	0.5	7	9
0.0	0.0	14	14
0.0	0.0	14	14

Appendix C

Listing for Program MAN and Required Data

```
      PROGRAM MAN (INPUT,OUTPUT)
      DIMENSION          T(14),TSET(14),TE(14),QCONV(13),QCOND(13),RE(13),
     1                   QMET(13),TEST(14),WARM(14),COLD(14),HC(14),A(14),
     1                   C(14),QLAT(14),QSEN(14),QRAD(14),QLCG(14),
     1                   HP(14),TWALL(14),EMIS(14)
 214  READ 301,   WORK,DTIME,TLM
      PRINT 305, WORK
      READ 302, IPRINT
 302  FORMAT(I5)
      READ 301, PCAB, TCAB, TDEW, RHOG, CPGAS, VCAB
      PRINT 304, PCAB,TCAB,TDEW,RHOG,CPGAS,VCAB
      DO 300 I=1,14
 300  READ 301,  T(I),TSET(I),TE(I),HC(I),A(I), C(I),TWALL(I),EMIS(I)
 301  FORMAT (8F10.5)
      READ 301, TEN
      PRINT 306, TEN
      DO 303 I=1,14
      TWALL(I)=TEN
  303 TE(I)=TEN
      TIME=0.0
      RMET=WORK+284.0
      GO TO 210
C
C
C
C     EVAPORATION
C     CALCULATE SWEAT AND SHIVER
 212  DO 52 I=1,14
      TEST(I)=T(I)-TSET(I)
      WARM(I)=0.
      COLD(I)=0.
      IF (TEST(I))53,54,55
 53   COLD(I)=-TEST(I)
 54   GO TO 52
 55   WARM(I)=TEST(I)
 52   CONTINUE
C
      WARMS=.056*WARM(2)+.276*WARM(5)+.173*WARM(7)+.043*WARM(9)+.383*
     1WARM(11)+.069*WARM(13)
      COLDS=.056*COLD(2)+.276*COLD(5)+.173*COLD(7)+.043*COLD(9)+.383*
     1COLD(11)+.069*COLD(13)
      WARMM=.417*WARM(4)+.19*WARM(6)+.393*WARM(10)
      COLDM=.417*COLD(4)+.19*COLD(6)+.393*COLD(10)
      SWEAT=WARM(1)*(WARMS+WARMM)*73.4814
      DILAT=SWEAT/4.
      QSHIV=COLD(1)*(COLDS+COLDM)*73.4814
      STRIC=(COLDS+COLDM)*.01961
C
C     RESPIRATION
      TRES=0.5*(T(1)+T(3))
      QLAT(1)=0.5*1040.0*0.0418*RHOG*RMET*(VPP(TRES)-0.8*VPP(TDEW))
     1*18.0/(29.0*PCAB)
      QRSEN1=0.5*0.0418*RHOG*RMET*CPGAS*(TRES-TCAB)
      QRSEN3=QRSEN1
C
```

```
C
      QLAT(3)=QLAT(1)
C     QLATENT FOR EACH OF THE SKIN NODES
      QLAT(2)=0.1*SWEAT
      QLAT(5)=0.6*SWEAT
      QLAT(7)=0.1*SWEAT
      QLAT(9)=0.02*SWEAT
      QLAT(11)=0.16*SWEAT
      QLAT(13)=0.02*SWEAT
      CEVAP=0.126*SQRT(VCAB/PCAB)*(TCAB+460.0)**1.04
      Z=VPP(T(2))-VPP(TDEW)
      QLAT(2)=QLAT(2)+6.66*A(2)*Z
      EMX=CEVAP*A(2)*Z
      IF(QLAT(2).GT.EMX) QLAT(2)=EMX
      DO 56 I=5,13,2
      Z=VPP(T(I))-VPP(TDEW)
      QLAT(I)=QLAT(I)+6.66*A(I)*Z
      EMX=CEVAP*A(I)*Z
      IF(QLAT(I).GT.EMX) QLAT(I)=EMX
 56   CONTINUE
C
C     QMET IS BASAL METABOLIC FOR ALL NODES EXCEPT MUSCLE NODES WHICH
C     ARE AFFECTED BY WORK
      QMET(1)=49.2825
      QMET(2)=0.3968
      QMET(3)=179.3536
      QMET(4)=17.0624+.417*(WORK+QSHIV)
      QMET(5)=2.0236
      QMET(6)=6.19+.190*(WORK+QSHIV)
      QMET(7)=1.23
      QMET(8)=2.3014
      QMET(9)=.3174
      QMET(10)=18.5702+.393*(WORK+QSHIV)
      QMET(11)=2.8172
      QMET(12)=4.5235
      QMET(13)=.4761
C
C     BLOODFLOW (IN POUNDS/HR)
      BF(1)=105.897
      BF(2)=2.647+.056*DILAT
      BF(3)=503.013
      BF(4)=22.062+QMET(4)-STRIC
      BF(5)=2.2062+.3*DILAT-STRIC
      BF(7)=1.103+.2*DILAT-STRIC
      BF(8)=1.103-STRIC
      BF(9)=8.824+.1*DILAT-STRIC
      BF(6)=6.618+QMET(6)+BF(9)-STRIC
      BF(11)=2.206+.294*DILAT-STRIC
      BF(12)=2.206-STRIC
      BF(13)=6.618+.05*DILAT-STRIC
      BF(10)=17.649+QMET(10)+BF(13)-STRIC
C     CHECK FOR NEGATIVE BLOOD FLOW
      DO 32 I=1,13
 32   IF (BF(I).LT. 0.) BF(I)=0.
C
```

```
C      QCONV(I)=CONVECTION FROM BLOOD TO EACH NODE
       DO 40 I=1,13
 40    QCONV(I)=BF(I)*(T(14)-T(I))
C
       QCOND(1)=5.798*(T(1)-T(2))
       QCOND(3)=10.691*(T(3)-T(4))
       QCOND(4)=29.759*(T(4)-T(5))
       QCOND(6)=9.699*(T(6)-T(7))
       QCOND(8)=6.349*(T(8)-T(9))
       QCOND(10)=9.435*(T(10)-T(11))
       QCOND(12)=4.762*(T(12)-T(13))
C
       DO 200  I=1,13
 200   QSEN(I)=HC(I)*A(I)*(T(I)-TE(I))
       DO 100 I=1,13
       TSZ=T(I)+460.0
       TWZ=TWALL(I)+460.0
       HR(I)=0.1713E-8*EMIS(I)*(TSZ**3+TSZ*TSZ*TWZ+TSZ*TWZ*TWZ+TWZ**3)
       QRAD(I)=HR(I)*A(I)*(T(I)-TWALL(I))
 100   QLCG(I)=0.0
C      QSEN =CONVECTION TO GAS
C      QRAD =RADIATION
C
C
C      CALCULATE TEMP OF HEAD CORE,T(1), AND TRUNK CORE,T(3)
       T(1)=T(1)+DTIME/C(1)*(QMET(1)-QLAT(1)+QCONV(1)-QCOND(1)-QRSEN1)
       T(3)=T(3)+DTIME/C(3)*(QMET(3)-QLAT(3)+QCONV(3)-QCOND(3)-QRSEN3)
C
C      CALCULATE TEMP OF SKIN --HEAD(2), TRUNK(5), ARM (7), HAND(9),
C      LEG(11), FOOT(13)
       T(2)=T(2)+DTIME/C(2)*(QCOND(1)+ QMET(2)-QLAT(2)+QCONV(2)-QSEN(2)
     1 -QRAD(2)-QLCG(2))
       DO 11 I=5,13,2
  11   T(I)=T(I)+DTIME/ C(I)*(QCOND(I-1)+ QMET(I)-QLAT(I)+QCONV(I)-QSEN(I
     1)-QRAD(I)-QLCG(I))
C
C      CALCULATE TEMP OF MUSCLE --TRUNK(4), ARM(6), HAND(8), LEG(10), FOOT(12)
       T(4)=T(4)+DTIME/C(4)*(QCOND(3)+QMET(4)+QCONV(4)-QCOND(4))
       DO 12 I=6,12,2
       T(I)=T(I)+DTIME/ C(I)*(QMET(I)+QCONV(I)-QCOND(I))
 12    CONTINUE
C
C      CALCULATE TEMP OF CENTRAL BLOOD(14)
       SQCONV=0.
       DO 13 I=1,13
 13    SQCONV=SQCONV-QCONV(I)
       T(14)=T(14)+DTIME/C(14)*SQCONV
C
       TIME=TIME+DTIME
       IF  (IP.EQ.IPRINT) 210,211
 211   IP=IP+1
       GO TO 212
 210   IP=1
  305 FORMAT (1X,*WORK EQUALS*,1X,F10.1)
  306 FORMAT (1X,*TEN EQUALS*,1X,F10.2)
```

```
304   FORMAT(1X,*PCAB,TCAB,TDEW,RHOG,CPGAS,VCAB EQUALS*,1X,6F10.4)
      PRINT 213, TIME,(T(I),I=1,14)
213   FORMAT(1X,*TIME EQUALS*,1X,F15.5/1X,*T(1) THROUGH T(7)*,1X,7F15.5
     1/1X,*T(8) THROUGH T(14)*,1X,7F15.5)
      IF(TIME.LT.TLM)  GO TO 212
      TIME=0.0
      WORK=3151.0
      PRINT 305, WORK
      READ 301, TEN
      PRINT 306, TEN
      DO 400 I=1,13
      TWALL(I)=TEN
  400 TF(I)=TEN
      GO TO  212
      END
      FUNCTION  VPP(T)
      Z=T+460.0
      VPP=0.178*EXP(9583.0*(0.0019608-1.0/Z))
      RETURN
      END
```

```
C     DATA FOR PROGRAM MAN.
C
  400.0    0.0003125 2.0
  160
 14.7      70.0      55.0      0.0761    0.238     40.0
  98.51    98.46     75.0      0.0       0.0       8.553     75.0      0.95
  95.03    96.12     75.0      1.829     1.5676    0.5511    75.0      0.95
  98.81    98.64     75.0      0.0       0.0       45.3004   75.0      0.95
  98.40    97.74     75.0      0.0       0.0       21.9337   75.0      0.95
  94.37    94.68     75.0      1.689     6.4544    2.8216    75.0      0.95
  98.17    96.84     75.0      0.0       0.0       8.5530    75.0      0.95
  91.45    93.24     75.0      2.072     3.5       1.7194    75.0      0.95
  96.65    97.56     75.0      0.0       0.0       3.2184    75.0      0.95
  95.98    96.84     75.0      2.072     0.5755    0.4408    75.0      0.95
  98.57    97.20     75.0      0.0       0.0       25.4608   75.0      0.95
  88.94    91.44     75.0      1.917     5.8       3.9017    75.0      0.95
  96.54    97.56     75.0      0.0       0.0       6.2825    75.0      0.95
  94.53    96.30     75.0      1.917     1.2128    0.6613    75.0      0.95
  98.53    98.10     75.0      0.0       0.0       2.7334    75.0      0.95
  82.4
  86.0
```

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